PHYSICAL CHARACTERIZATION OF INDOOR-OUTDOOR AIRBORNE PARTICLES IN THE TROPICS

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Table of Contents

Summary

Urban population is frequently exposed to high air pollution concentration, where motor vehicle emissions constitute the main source of fine and ultra fine particles. The exposure to particles is of concern since fine particles get deposited into the respiratory tract and can lead to various respiratory diseases and premature deaths. The infiltration of particles into the building will depend on the size of particle, filtration characteristics, properties of building envelope etc.

The objective of the research is to assess the particle concentrations at indoor and outdoor locations near major roads and to investigate the migration of particles by ascertaining I/O ratios. The effect of ambient environmental conditions on the migration phenomenon is also investigated. Studies have been carried out in residential apartments near major roadways to study the particle distribution at different building heights in a multi-storey building.

An intensive field study was carried out near one of the major expressways in Singapore to assess the physical characteristics of particles in terms of particle mass concentration, number concentration and particle size distribution. This study shows that –

- A significant linear correlation is observed between particle mass and particle count.

- PM_{10} (particles less than 10 microns) comprises almost 80 % of the total suspended particulate matter. It was observed that PM_1 gravimetrically comprises 60 ± 5 % of PM_{10}.
- The importance of particle count is also realized. The present study shows that fine particles comprise 99 % of the particle count. These fine particles can have severe health implications as they have the potential to penetrate deep into the respiratory system. Expressway is found to have higher concentration of fine particles as compared to other locations. This is mainly attributed to the vehicle generated combustion which is responsible for fine particles. Minor road and naturally-ventilated spaces have higher concentrations of larger size particles.
- Mechanically-ventilated office space showed a lower particle concentration both in mass and number as compared to all other locations. Particles in the coarse range were nearly absent and this shows the high efficiency of the filtration system. The characterization information can serve as useful criterion for filter selection.

The effects of environmental parameters like temperature, relative humidity and wind speed on the migration of particles was investigated. Findings revealed that temperature and wind speed have a positive influence while relative humidity has a negative influence on the migration of particles. With the increase in particle size their dependence on ambient parameters like temperature and relative humidity decreases significantly as compared to wind speed. In addition, temperature may be a dominant factor governing the migration of fine particles as compared to wind speed.

This study further revealed that the concentration of particles in a building varied with height, with first an increase in value, attains a maximum and then decreases. The difference in concentration for PM_1 was less as compared to PM_{10}. The highest fraction of coarse particles ($PM_{2.5-10}$) out of the suspended particulate matter (PM_{10}) is highest at the intermediate building height. The correlation between fine and coarse mode particles at the intermediate building height was comparatively weaker as compared to higher building heights. It was observed that the temperature and relative humidity were highest and wind speed was lowest at the intermediate building height.

List of Tables

List of Figures

Chapter 1: Introduction

1.1 General

There is a concern about airborne particles in the adverse environmental effects of air pollution, especially in urban agglomeration. This is reflected by a number of governmental measures, planned or carried out, around the world to curb the air pollution due to particles. The exposure to particles is critical since fine particles get deposited into the respiratory tract and can lead to various respiratory diseases and premature deaths. Exposure to fine and ultra fine particles could have relatively more significant health implications than exposure to larger particles or to other airborne pollutants. It was estimated that 6% of the deaths in Europe (1 in 17) could be blamed on particles caused by traffic fumes (**Colvile *et al*., 2003**).

1.2 Scope of work

The concern for the elevated concentrations of particles is mainly derived from the evidence of human health associated with atmospheric particles. The epidemiological literature has hundreds of published papers, which for the most part, support association of particles with increase in morbidity and mortality.

The research work focuses on particle concentration at different indoor and outdoor locations in Singapore. The characterization of particles both gravimetrically and in terms of numbers is an important step in the area of particle research. It is therefore important to characterize particles at different indoor and outdoor locations.

It is important to know the migration of particles and can be ascertained by determining Indoor-Outdoor ratios (I/O). The effect of environmental parameters on the migration of different size particles is crucial as these could be an important factor affecting the migration of fine and ultra fine particles.

Particle concentration will also vary with building height in a multi-storey building. It is therefore important to characterize particles gravimetrically and on the basis of number at different building heights to assess the variation of particle concentration as a function of building height.

1.3 Research Objectives

This research work aims to achieve the following main objectives:

- To assess the concentration of particles at different indoor and outdoor locations. Particle concentration will be measured both in terms of mass and number. It will include the importance of number density of particle over particle mass.

- To ascertain the migration of particles using Indoor-Outdoor ratios (I/O). The effect of ambient environmental condition on the migration phenomenon will be investigated by using simple statistics between I/O ratios and ambient wind speed, temperature and relative humidity.

- To study the variation of particle concentration at different heights of multi-storey buildings near major roads/expressway.

This research work will serve as an initiative in the field of particle science in Singapore, and provide a platform for future research.

1.4 Structure of thesis

Chapter 1 gives a brief introduction reflecting concern about airborne particles. It also highlights the scope of work and research objectives.

Chapter 2 lists some of the previous works done in the area. It also brings into account the different ways of characterizing the particles, associated health impacts, regulatory guidelines, and migration of particles to indoor spaces.

Chapter 3 discusses on the research methodology giving details about the experiment sites and instrumental details.

Chapter 4 deals with the characterization of particles. The results of the experiments highlight the importance of particle count over particle mass. It shows the size distribution at different indoor and outdoor locations.

Chapter 5 focuses on the migration of particles to the indoor spaces by calculating the Indoor-Outdoor ratio. It also presents the role of ambient temperature, relative humidity, and wind speed in the migration of particles.

Chapter 6 presents the characterization of particles at different building heights. It aims to look into the particle concentration at higher building heights compared to the lower building heights located near major expressways.

Chapter 7 lists the summarized conclusion along with the limitations of the present study and suggesting further improvements.

The end of the thesis is marked by the references and list of publications.

Chapter 2: Literature Review

2.1 Definition

Particles can be defined as “suspension of solid or liquid mass in air”. Particles can originate from a variety of sources and possess a range of morphological, chemical, physical and thermodynamic properties. The particles could be combustion generated, photo-chemically produced, salt particles from sea spray or even soil-like particles from re-suspended dust. Particles may be liquid; solid or could even be a solid core surrounded by liquid.

2.2 Characterization

2.2.1 General

Particles are represented by a broad class of chemically and physically diverse substances. Particles can be described by size, formation mechanism, origin, chemical composition, atmospheric behavior and method of measurement. The concentration of particles in the air varies across space and time, and is related to the source of the particles and the transformations that occur in the atmosphere. Some of the more generalized characterization of particles are:

Primary and secondary particles: A *primary particle* is a particle introduced into the air in solid or liquid form, while a *secondary particle* is formed in the air by gas-to-particle conversion of oxidation products of emitted precursors.

Particle characterization as per size: Particle can be classified into discrete size categories spanning several orders of magnitude, with inhalable particles falling into the following general size fractions- PM_{10} (equal to and less than 10 micrometre (µm) in aerodynamic diameter), $PM_{2.5-10}$ (greater than 2.5 µm but equal to or less than 10 µm), $PM_{2.5}$ (2.5 µm or less), and ultra fine (less than 0.1 µm).

Particle characterization depending on requirements of study: Some of the particle components/ parameters of interest to health, ecological, or radiative effects; for source apportionment studies; or for air quality modeling evaluation studies are listed below:

- Particle number
- Particle surface area
- Particle size distribution
- Particle mass
- Particle refractory index(real and imaginary)
- Particle density and particle size change with density
- Ionic Composition (sulphate, nitrate, ammonium), chemical composition, proportion of organic and elemental carbon, presence of transition metals crustal elements, etc.
- Bioaerosols

Table 2-1 shows the modal particle classification. It should be noted that combustion generated particles are in the fine range and have a higher life and can be transported to longer distances.

Table 2-1: Comparison of Ambient Particles, Fine Mode (nuclei mode plus accumulation mode) and Coarse Mode[1]

	Fine		Coarse
	Nuclei	Accumulation	
Formed from:	Combustion, high-temperature processes, and atmospheric reactions		Break-up of large solids/droplets
Formed by:	Nucleation Condensation Coagulation	Condensation Coagulation Reactions of gases in or on particles Reactions of gases in or on particles Evaporation of fog and cloud droplets in which gases have dissolved and reacted	Mechanical disruption (crushing, grinding, abrasion of surfaces) Evaporation of sprays Suspension of dusts Reactions of gases in or on particles
Composed of:	Sulfates Elemental Carbon Metal compounds Organic compounds with very low saturation vapor pressure at ambient temperature	Sulfate, Nitrate, Ammonium, and Hydrogen ions Elemental carbon Large variety of organic compounds Metals: compounds of Pb, Cd, V, Ni, Cu, Zn, Mn, Fe, etc. Particle-bound water	Suspended soil or street dust Fly ash from uncontrolled combustion of coal, oil, and wood Nitrates/chlorides from HNO_3/HCl Oxides of crustal elements (Si, Al, It, Fe) $CaCO_3$, NaCl, sea salt Pollen, mold, fungal spores Plant and animal fragments Tire, brake pad, and road wear debris
Solubility:	Probably less soluble than accumulation mode	Largely soluble, hygroscopic, and deliquescent	Largely insoluble and nonhygroscopic
Sources:	Combustion Atmospheric transformation of SO_2 and some organic compounds High temperature processes	Combustion of coal, oil, gasoline, diesel fuel, wood Atmospheric transformation products of NO_x, SO_2, and organic compounds, including biogenic organic species (e.g., terpenes) High-temperature processes, smelters, steel mills, etc.	Resuspension of industrial dust and soil tracked onto roads and streets Suspension from disturbed soil (e.g., farming, mining, unpaved roads) Construction and demolition Uncontrolled coal and oil combustion Ocean spray Biological sources
Atmospheric half-life:	Minutes to hours	Days to weeks	Minutes to hours
Removal Processes:	Grows into accumulation mode	Forms cloud droplets and rains out Dry deposition	Dry deposition by fallout Scavenging by falling rain drops
Travel distance:	<1 to 10s of km	100s to 1000s of km	<1 to 10s of km (100s to 1000s in dust storms)

[1] **Wilson and Suh (1997)**

2.2.2 Importance of particle number concentration

Particles can be characterized in a number of ways. However, it is usually reported in gravimetric terms. Studies have shown that particle count can be more significant as small sized particle comprise small in mass but large in numbers.

There is a strong indication that the adverse health effects of particles may not be due mainly to particle mass, but instead particle number concentration **(Penttinen et al., 2001a)**. For instance, a study on characterization of airborne particles in Beijing **(Shi *et al*., 2003)** showed that:

- 99% of airborne particles are in PM_{10} and $PM_{2.5}$ range,
- about 94% dust storm particles are in the respirable fraction, and
- a roadside PM_{10} study revealed that particles less than 1 µm accounted for 98% of total suspended particles.

Similarly, in another study in China **(Wu et al., 2002)** the daytime averaged $PM_{2.5}$ and PM_1 constituted 66-67 % and 51-60 % respectively, of the total PM_{10} mass.

High number concentrations of fine and ultrafine particles in urban environments, especially in the vicinity of major streets and roads **(Buzorius et al., 1996; Morawska et al., 1999; Pakkanen et al., 2001)**, raise an interest to study the physical and chemical transformation of particles.

2.3 Environmental Impacts

Particles can have health impacts, reduced visibility and environmental degradation as listed below.

2.3.1 Health effects

Many scientific studies have linked particles to a series of significant health problems, including:

- aggravated asthma
- increases in respiratory symptoms like coughing and difficult or painful breathing
- chronic bronchitis
- decreased lung function
- premature death

A major contribution to pollution due to particles in urban areas is believed to be attributed to traffic and especially to emissions from diesel fuelled vehicles. Fine particles emitted from petrol as well as diesel engines are formed at high temperature in the engines, in the exhaust pipe, or immediately after emission to the atmosphere. Some of these particles may be in the so called nucleation mode. These particles are often formed by coagulation of primary particles, and by condensation of gases on particles. The fine particles (accumulation mode in the range 0.1–2 µm) are typically secondary particles formed by chemical reactions (e.g. SO_2 and NO_x to form sulphates and nitrates), or other relatively slow processes in the atmosphere. The coarse mode of particles are >2 µm, which in urban areas typically are formed mechanically by abrasion of road material, tyres and brake linings, soil dust raised by wind and traffic turbulence, etc. These coarse particles may also cause health effects. The fine and ultra fine particles will be deposited deep in the lungs and the residence time will be very long, up to several months **(WHO, 2000)**. The chemical and physical properties are important for assessment of deposition in the lungs and assessment of the adverse health effects as the deposition is strongly influenced by water uptake of the particle in the humid lungs. The size of airborne particles is significant as it determines their dynamic properties and thus behaviour in the air and fate during transport and in particular, strongly influences in which part of the respiratory tract the particles are deposited. Larger particles, due to their higher inertia are deposited in the nasal area and in the upper parts of the respiratory tract. By contrast, smaller particles that can follow the airflow to the deeper parts of the respiratory tract have a very high probability of depositing in those parts by diffusion, which is a very efficient deposition mechanism for small particles.

The important properties—in addition to size—are state (liquid/solid), volatility, hydroscopicity, chemical composition (content of organics, metals, salts, acids etc.), morphology, and density. These properties are also important for selection of methods for regulation and control of emissions.

Numerous epidemiological studies have shown statistically significant associations of ambient particle levels with a variety of human health endpoints, including mortality, hospital admissions, emergency department visits, other medical visits, respiratory illness and symptoms and physiologic changes in pulmonary function. Associations have been consistently observed between short- and long term particles exposure.

Hoek *et al*. (1998) discovered that a 10 µg/m^3 increase in PM_{10} is associated with a 10% decrement in children's peak expiratory flow. The estimated increase in the relative rate of death from cardiovascular and respiratory causes was 0.68% for each increase of 10 µg/m^3 in the PM_{10} level **(Samet *et al.*, 2000)**. Many studies consistently show the direct link between mortality rates and daily ambient concentrations of suspended matter that have diameter below 10 µm. According to the health statistics issued by the Ministry of Health, Singapore **(Ministry of Health Singapore report, 2001)**, 24 % of the total deaths in 2002 (preliminary statistics) were due to cardiovascular diseases and 0.7% of the total deaths were due to bronchitis, emphysema and asthma.

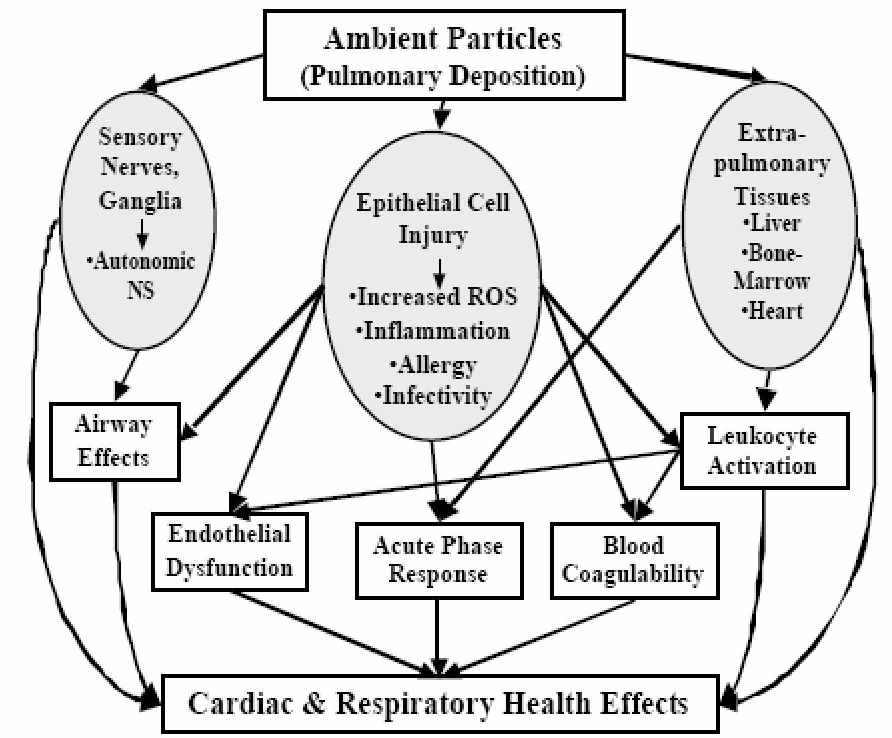

Figure 2-1 Hypothesis for Health effects of Particles[2]

Figure 2-1 highlights the complexity and interdependency of some of these pathways in the human body affected by particles **(Utell and Frampton, 2000)**. The portal for air pollution caused by particles is the lung. Particles interactions with respiratory epithelium likely mediate a wide range of effects, as indicated by the central oval in Figure 2.1. These include respiratory as well as systemic and cardiovascular effects. However, particles, or its reaction products, may stimulate airway sensory nerves, leading to changes in lung function and in autonomic tone, which influences cardiac function.

[2] **Utell and Frampton (2000)**

Large-size particles mainly deposit in the upper part of the respiratory tract due to impaction, interception, gravitational sedimentation, as well as turbulent dispersion. Very fine particles, such as generated through combustion processes, have a high probability of deposition in deeper parts of the respiratory tract, due to their high diffusivities. Ultra fine particles, by virtue of their extremely small size, may enter pulmonary capillary blood and be rapidly transported to extra pulmonary tissues, such as liver, bone marrow, and heart, with either direct or indirect effects on organ function.

It has been postulated that ultra-fine particles have the ability to penetrate lung walls inducing inflammation in the pulmonary interstitum, which in turn stimulates the production of clotting factors in the blood responsible for the recognized ability of airborne particles to exacerbate ischaemic heart disease **(Seaton *et al.*, 1995)**. One of the more interesting findings from the toxological studies suggests that ultra-fine particles of less than 100 nanometre (nm) have considerably enhanced toxicity per unit mass and that their toxicity increases as particle size decreases **(Donaldson and Macnee, 1998)**. This may be attributed to the fact that fine/ultra-fine particles have higher surface area per unit mass.

However many difficulties still exist in this area, such as difficulties in:

- delineating the magnitudes and variabilities of risk estimates for ambient particles,
- the ability to attribute observed health effects to specific particle constituents, the time intervals over which particle health effects are manifested,

- the extent to which the findings in one location can be generalized to other locations, and
- the nature and magnitude of the overall public health risk imposed by ambient particle exposure.

Ongoing research in particle science is devoted towards finding answers to these issues.

2.3.2 Visibility impairment

Particles are the major cause of reduced visibility (haze) in Singapore. Singapore is likely to be impacted by smoke haze when there are forest fires in the region and the prevailing Southwest Monsoon winds blow the smoke from the fires towards Singapore. The highest PSI recorded by National Environment Agency, Singapore was 142 in September 1994. Also, the highest PSI recorded in last five years (1999 – 2003) was 92 and the pollutant responsible for such a high PSI was PM_{10}. These facts show that particles are really a pollutant of concern in Singapore.

2.3.3 Atmospheric deposition

Particles can be carried over long distances by wind and then settle on ground or water. The effects of this settling include-

- making lakes and streams acidic

- changing the nutrient balance in coastal waters and large river basins
- depleting the nutrients in soil
- damaging sensitive forests and farm crops
- affecting the diversity of ecosystems

2.3.4 Aesthetic damage

Particles stain and damages stones and other materials, including culturally important monuments and statues. These particles may be acidic or alkaline in nature. In highly urbanized settings, soot generated by traffic pollution is responsible for damaging and deteriorating the building and decreasing structural life.

2.4 History of Air Quality Standards of Particles

Particle standards, unlike those for other criteria pollutants, are not specific to a particular chemical, but simply specify the particle mass concentration regardless of chemical composition.

Air quality and sampling standards for particles in the United States were first set in 1971. The standard sampling method collected what is known as total suspended particulate (TSP) by sampling with a high-volume (hi-volume) sampler that draws air through a large filter at about 50 cubic feet per minute. The air quality standard required an annual average concentration of less than 75 micrograms of particles per cubic meter of air ($\mu g/m^3$).

The sampling pump and filter used for TSP sampling were enclosed in a peaked-roof enclosure to protect it from the weather. The filter had high efficiency for all particle sizes, but the enclosure caused a variable collection efficiency of larger size particles, those in the range from 20 to 50 µm, that was dependent on wind velocity and direction. This gave variable measurements of particle mass concentration that did not reflect the health risk to humans.

To overcome this problem US EPA promulgated PM_{10} ambient air quality standards and sampling criteria in 1987. Particles that meet the PM_{10} criteria are those less than 10 µm and represent a portion of the TSP particles. An aerodynamic separator in the sampler inlet selects those particles that meet the PM_{10} criteria while they are still airborne. The PM_{10} standard requires communities to achieve an annual average concentration of PM_{10} particles of less than 50 $\mu g/m^3$.

PM_{10} sampling has two advantages:

- a well defined upper limit which is not affected by wind velocity or direction; and
- a well defined health basis, namely collection of particles able to pass though the mouth, nose and throat and reach the lungs.

This more precise type of measurement permitted the discovery of health effects due to particle air pollution that had been masked by the variability of the TSP method.

One limitation of PM_{10} is that the sampled particles contain the entire fine particle mode and a portion of the coarse particle mode. These two modes have different sources and chemical composition and therefore it is difficult to separate the role of different chemicals in air pollution due to particles and to determine the sources of those particles that cause the health effects. Information is needed to implement effective control strategies. In 1997 the US EPA adopted additional standards and sampling methods for particles less than 2.5 µm ($PM_{2.5}$). The new standard for $PM_{2.5}$ is an annual average of 15 $\mu g/m^3$. The cut-off at 2.5 µm is approximately at the saddle point between the coarse and fine particle modes and thus provides samples of fine particles relatively uncontaminated with coarse particles. The more recent standards defined in terms of particle size can be thought of as a subset or fraction of earlier standards. Thus, $PM_{2.5}$ is a subset of PM_{10} and PM_{10} is a subset of TSP. New sampling method focuses in more closely on those particle sizes and chemical compositions that are believed to affect human health.

2.5 Singapore Air Quality

In Singapore, as in any other highly urbanized city, motor vehicle emission is a significant source of air pollution. Vehicular emissions generally consist of carbon monoxide, ozone, nitrogen oxides, sulphur dioxide and particles. Levels of air pollutants generated by vehicular emission are usually low and well within the ambient air quality standards set by

World Health Organization (WHO) and the primary air quality standards of the United States Environmental Protection Agency (USEPA). These standards are used to assess the ambient air quality in Singapore. The Pollutant Standard Index (PSI), an indicator of the ambient air quality developed by the USEPA is recorded daily. The PSI usually varies from 20 to 50 indicating good level of air quality.

2.6 Particle Migration

2.6.1 Indoor vs. Outdoors

People spend most of their time indoors. The outdoor environment can have significant impact on the air quality inside naturally-ventilated and mechanically-ventilated building. Hence in today’s context, a building should not only be structurally sound but also provides a healthy environment for the occupants to work and live in.

The infiltration of particles into the building will depend on the size of particle, filtration characteristics, properties of building envelope etc. Knowledge of ambient pollutant concentration can help in determining the indoor pollutant concentration. This can help in designing ventilation strategies for a naturally-ventilated building and selecting the fresh air intake point for mechanically-ventilated buildings.

The outdoor air quality has a significant effect on indoor air pollution levels, and occupants spend most of the time indoors. Motor vehicle emission affect not only ambient air quality but also the indoor air quality, infiltrating buildings through open windows, doors, through the building envelope and penetration of mechanical filtration system. Knowledge about the influence of ambient air pollution on the concentration in indoor environment is, therefore, crucial for assessment of human health effects from traffic pollution. Concurrent indoor and outdoor 10-minute averaged $PM_{2.5}$ and PM_{10} concentrations to establish the correlation for indoor–outdoor particles for typical West Texas residences equipped with evaporative coolers showed that if the ambient particle concentration remains steady, a 10-minute average indoor air sample after the first 10-minute period would consist of 99% outdoor air and a 1-hour average indoor air sample would actually consist of 95% of the outdoor air. In addition, a strong diurnal pattern of PM_{10} indoor and outdoor was observed in nine out of the 10 houses tested independent of the possible human activities and other indoor sources at each residence **(Wen-Whai *et al*., 2003)**. Studies conducted by researchers **(Morawska *et al*., 2001; Chao and Wong, 2002)** show that outdoor particle concentration could be used to predict indoor concentration.

In a well-sealed mechanically-ventilated building, the majority of outside air enters through prescribed inlets and **Green and Etheridge (1998)** showed that the indoor air quality can be significantly improved by drawing air from less contaminated sides of the building. In the case of naturally-ventilated buildings, infiltration is a function of wind and buoyancy pressures acting across the envelope and characteristics of flow path between the inside and outside of the building (**CIBSE, 1997).**

Thompson *et al.* (1973) reported I/O ratios of total suspended particles (TSP) as low as 0.1 in air-conditioned buildings with substantial filtration compared with I/O ratios greater than unity in naturally-ventilated buildings with substantial foot traffic. Comparative studies of naturally-ventilated and mechanically-ventilated spaces tend to draw the conclusion that the I/O ratio is generally higher in naturally-ventilated buildings than mechanically-ventilated buildings.

Detailed knowledge of particle characterization can even help in the selection of suitable filter for mechanically-ventilated buildings. Apart from the outdoor particle concentration, the migration of particles to indoors can be affected by the ambient environmental conditions like temperature, relative humidity, wind speed and wind direction.

2.6.2 Role of Ambient Environment in Particle Migration

The particle concentration in urban areas has different characteristics on account of the changing meteorological factors depending on the geographical and topographical peculiarities of the urban areas. Many papers discuss the influence of these meteorological parameters on air pollution concentration. **Miyazaki and Yamaoka (1990/1991)** investigated the relation of mean dust concentration in air with several meteorological factors (e.g. precipitation and wind speed) in Osaka city. According to the results of **Tirabassi et al. (1990/91)**, there is a close relationship between wind speed and pollutant ground-level concentration in the coastal city of Ravenna. **Cuhadaroglu and Demirci (1997)** investigated the influence of some meteorological factors on air pollution in Turkey and found that the suspended particle concentration increased with increasing temperature and decreased with decreasing humidity. These studies mark the role of ambient meteorological parameters and how they can effect the ambient concentration. Also, it stresses that ambient concentration is also a function of these meteorological parameters.

However there are still very few studies which relate the migration of these particles to indoor spaces with the ambient parameters. The environment which acts as a medium for the transport, and any change in meteorological conditions will definitely affect the transport of particles. Hence, factors like ambient temperature and relative humidity, wind speed and wind direction can play an important role in migration of particles. Aerosol particles, mainly water soluble change their size as a function of the humidity of air **(Ferron, 1977)**. The change in size will affect the transport phenomenon of particles.

2.7 Vertical Transport of Particles in Buildings

Variations in concentration of particles depend on several factors which include vehicle generated turbulence, variation in traffic flow, meteorological parameter and geometry of the street. The dispersion will also depend upon the street configuration and shape of the building. **Qin and Kot (1993)** measured typical street canyons in Guangzhou City, which compared the air dispersion in different types of road in urban canyons and its result indicates that the configuration of a street is an important factor that influences air dispersion. Street measurements are also influenced by local conditions and care must be taken in the interpretation of their results, in the estimation of urban air pollution levels and in comparing air quality in different cities **(Ruwin et al., 1996)**.

In Singapore, due to lack of space, buildings are usually in the form of high-rise towers and they are in close proximity. Some of the residential apartments are even located very close to the expressways, which have a very high traffic volume and most of these apartments are naturally ventilated. To assess the exposure, it is necessary to know the contribution of arterial roads to particle concentration in its vicinity. Apart from this the knowledge of I/O ratio, variation of particle concentration around the building envelope and in particular the variation above the ground helps in designing mitigation measures and to minimize exposure to these particles.

There are many studies being carried out by researchers to study the vertical transport of particles **(Morawska et al., 1998; Wu et al., 2002)**. In a study in Hong Kong **Chan and Kwok(2000)** found that in street canyons the distribution of TSP and PM_{10} concentration varies exponentially with height where as there is no fixed pattern for buildings in open street. The larger size particles are greatly affected by gravity and the fine particles are more affected by diffusion. For a building in open street, the vertical concentration will depend on vertical mixing, local dilution, and other external factors such as sea breeze, as well as proximity to major road.

CHAPTER 3: Methodology

3.1 Introduction

Singapore is a highly urbanized city in the Tropics with a well developed transportation system characterized by expressways and mass rapid transit systems to facilitate fast and swift movement of people and other utilities. However, every advantage is associated with some drawbacks. The large volume of traffic on these expressways and other transportation systems is responsible for the generation of air pollutants like carbon monoxide (CO), oxides of nitrogen and sulphur (NO_x , SO_x) and particles. Particle is not a specific chemical entity but consists of different sizes, composition and properties.

3.2 Theoretical Framework

Researchers all over the world have stressed the significance of particle characterization and importance of particle number concentration **(Buzorius et al., 1996; Morawska et al., 1999; Pakkanen et al., 2001)** in the urban environment especially in the vicinity of major road. In ambient environment concentrations of small particles are usually significantly higher than concentrations of larger particles **(Morawska et al., 1998)**, and it thus appears that for health risk assessments, knowledge of particle number concentrations could be more important than knowledge of particle mass **(Oberdorster et al., 1994; Seaton et al., 1995; Li et al., 1996)**. The main disadvantage of using particles mass standards is that the value of concentrations is biased towards larger sized particles despite their lower number density. In addition, the atmospheric deposition rates and residence time in the atmosphere are a strong function of their aerodynamic diameters. The aerodynamic diameter also influences the deposition patterns of particles in the lungs. The effect of atmospheric particles on visibility, radiative balance, and climate are influenced by the size distribution of particles. Hence quantification in terms of particle count seems more appropriate than the mass concentration in the case of particles.

The relationship between particle number and mass concentrations is of particular importance **(Morawska, 1999)** New research efforts are now often directed towards experimental characterization of particle number distribution in order to relate the results to the current standards. Attempts have been made to establish correlation between particle mass and particle number concentration in terms of coefficient of determination (**Roy *et al.*, 1999)**. Coefficient of determination (R^2) is a commonly used measure of the goodness of fit of a linear model which is defined as the proportion of the variation in the dependent variable.

Study conducted along road sides **(Jones and Harrison, 1994)** have revealed that the concentration of fine particles are much greater closer to the sources such as vehicular traffic, than that at more distant locations. Study conducted by **Li et al. (1993)** showed that higher level of particles coincided mostly with peak traffic hours where as lowest particle number concentration occurred in the absence of traffic activity. Hence experimental sites located close to road ways and expressways will be the most ideal locations to assess the maximum possible concentrations with sampling interval as peak traffic hours.

The studies attempting to explain the behavior of ambient particles under different environmental conditions have taken up simple statistical approach, using parameters like mean, median and standard deviation to describe variations in particle numbers; and multiple linear regressions to establish a cause-effect relationship**.**

Cuhadaroglu and Demirci (1997) studied the effect of meteorological data such as wind speed, relative humidity and temperature on particle concentration in Turkey using multiple regressions between particle concentration and meteorological.

A general regression equation which has three or more variables can be expressed as:

$$Y = A + B_1X_1 + B_2X_2 + B_3X_3 + E$$

Where A is the constant of regression and B is the coefficient of regression. The particle concentration is considered as dependent variable while temperature, relative humidity and wind speed are independent variables. The values of the constant and the coefficient are determined using the least square method which minimizes the error appearing as E in the above regression equation.

However the study by **Cuhadaroglu and Demirci (1997)** was for predicting the particle concentration, similar statistical approach was used to study the variation of Indoor–

Outdoor ratio as dependent variable and temperature, relative humidity and wind speed as dependent variable.

Such studies are therefore necessary and the results vary from region to region. The particles have the tendency to coagulate and form larger size particles in the regions characterized by high relative humidity. Hence such studies are necessary in a tropical country like Singapore. In such conditions, detailed size characterization is necessary for studies on health effects and assessment of level of penetration to the buildings.

The vertical dispersion of particles is studied by various researchers all over the world. **Chan and Kwok (2000)** studied the variation of particle concentration in different land type pattern (New town and Harbor front) in open street configurations. The site environment selected by them had low traffic, 5-7 floors high and sampling was carried out at three points (7, 10 and 18 m in building at New town; 3, 8 and 25 m in building at Harbor front). Studies were conducted by **Morawska (1999)** on three different buildings located at 15(building 1), 80 (building 2) and 210 m (building 3) from the freeway and particle concentration was measured at different heights (Building 1 - 3, 5 and 11 m; Building 2 - 2, 4, 6 and 8 m; Building 3 - 3, 5, 10, 15, 20 and 25 m). Vertical profile measurements revealed no significant correlation between particle concentration and height; however for buildings in the immediate proximity to the arterial road (about 15 m) concentrations around the building envelope were very high, comparable to those in the immediate vicinity of the road, indicating undiluted concentrations. In Singapore, many tall buildings (12 storeys) are located close to major expressways. Hence it is important to study the particle concentrations and characterize particles at such sites.

Studies on particles vary from region to region as particle behavior and characteristics are affected by numerous factors discussed earlier. Hence a regional analysis based on specific requirements is necessary. Singapore, highly urbanized, with limited land resources and characterized by a tropical climate presents a different case for the study of particles. The present study is an attempt to generate some base line information about particle concentrations in outdoors and indoors as well as their behavior in the atmosphere, so that detailed studies could follow to explain specific findings during this work.

3.3 Research Design

The important decisions that were required in this research are:

- Selection of suitable sites and instruments
- Designing a suitable methodology for carrying the experiments
- Analyzing the experiment results using statistical methods.

The following methodology is designed after carrying out some preliminary experiments and using the available facilities. The experiments were scheduled in three phases.

Phase 1: Experiments to determine the ambient particle concentration at expressway.

Phase 2: Experiments to assess the migration from outdoor to indoor location and compare particle concentration at these locations.

Phase 3: Experiments to analyze the particle distribution with respect to height.

3.3.1 Instrumentation

Experiments require measurement of particle count across different size ranges and particle mass. It also requires measurement of ambient temperature, relative humidity, wind speed and wind direction. The traffic volume was obtained from the Land and Transport Authority, Singapore.

To measure the particle count and particle mass, Grimm Dust Monitor 1.108 and Dust Trak (Model 8520) were used. Grimm Dust monitor and Dust Trak have been used by many researchers for similar studies **(Micallef et al.,1998;Wu et al.,2002)**. Temperature and relative humidity measurements were carried out using Hobo meter. Wind speeds and wind directions were obtained from the nearest weather station. Instantaneous onsite wind speeds were measured using Kanomax Anemomaster.

3.3.1.1 Grimm Dust Monitor

The dust monitor is based on the principle of quantifying the angular dispersion or scattering of light caused by the passage of particles of various sizes through a light beam produced by a laser diode. The sheath air rate is 0.2 L/min. The instrument records the particulate matter both in terms of mass and number.

Table 3-1 Technical Specification of Grimm Dust Monitor (Model 1.108)

Sensor Type	*90^o light scattering, laser diode*
Range	*0.1-100 000 µg/m^3* *1-2 000 000 counts/litre*
Sensitivity	*1 particle/litre*
Particle size	*0.30/0.40/0.50/0.65/0.80/1.0/* *1.6/2.0/3.0/4.0.5.0/7.5/10/15/20 µm*
Flow rate	*1.2 L/min*

Figure 3-1 Grimm Dust Monitor

3.3.1.2 Dust Trak

The dust monitor can give mass in terms of PM_{10}, $PM_{2.5}$ or PM_1 by changing the inlet. It works on the principle of light scattering. Table 3-2 illustrates the sensitivity of the instrument. Figure 3-2 shows the Dust Trak Aerosol Monitor (Model 8520).

Table 3-2 Technical Specification of Dust Trak (Model 8520)

Sensor Type	*90^o light scattering, laser diode*
Range	*0.001-100mg/m^3*
Resolution	*±0.1 % of reading or ±0.001 mg/m^3 whichever is greater*
Particle size range	*0.1 – approximate 10 µm (upper limit is dependent on flow rate)*
Flow rate range	*1.4 – 2.4 L/min*

Figure 3-2 Dust Trak

3.3.1.3 Hobo meter

The instrument, with built in data logger, can record temperature and relative humidity. It measures relative humidity and temperature to an accuracy of one decimal place.

The relative humidity sensor's operating range is 25% to 95% at 77^{o}F and for sampling intervals of 10 seconds or longer. It should be noted that the Hobo's RH sensor can be damaged by condensation. So it must not be exposed to fog, mist or other condensing conditions.

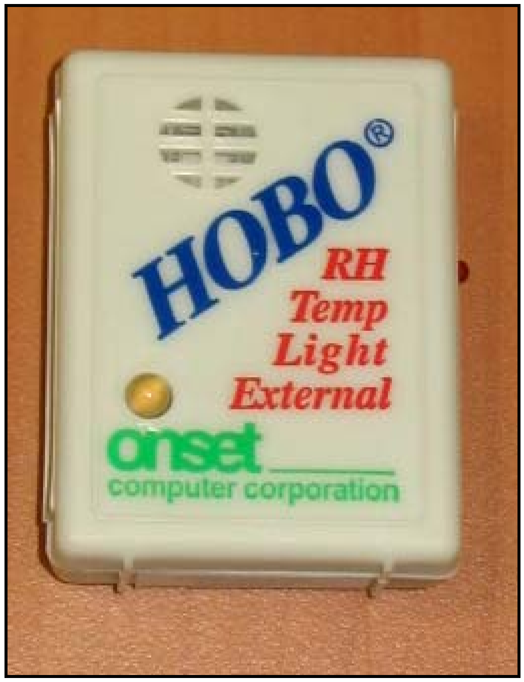

Figure 3-3 Hobo meter

Each HOBO H8 logger has an internal temperature sensor on a 4 inch wire which is mounted on the circuit board inside the snap lid case. Typically, the sensor is left inside the case and measures ambient air temperature over the operating range of logger; - 4 ^{o} F to 158 ^{o} F (-20 ^{o} C to 70 ^{o} C) with a time constant of about 15 minutes in still air. The internal sensor can be placed outside the case when a shorter time constant is needed (less than 1 minute in air and about 2 seconds in water). The temperature sensor is capable of measuring temperatures from -40^{o}F to + 248^{o}F (-40^{o}C to 120^{o}C) when extended from the case.

3.3.1.4 Kanomax Anemomaster

Kanomax Anemomaster(Model 6004) is used to measure wind speed. It can measure wind speed in the range of 0.1 and 20 m/s to an accuracy of ± (5% of readings + 0.1m/s). The instrument is based on the working principle of hot wire anemometer.

Figure 3-4 Kanomax Anemomaster

3.3.1.5 Weather Station

The National University of Singapore (NUS) weather station serves primarily academic needs and is maintained by the Department of Geography. The station is located on the rooftop of building E-2 (Faculty of Engineering) of the National University of Singapore, Kent Ridge campus, near the South coast about 9 km west of the city center. The weather station is located at a height of 90 metres above sea level. The geographical coordinates are approximately: 1 deg18 min N (latitude) and 103 deg 46 min E (longitude).

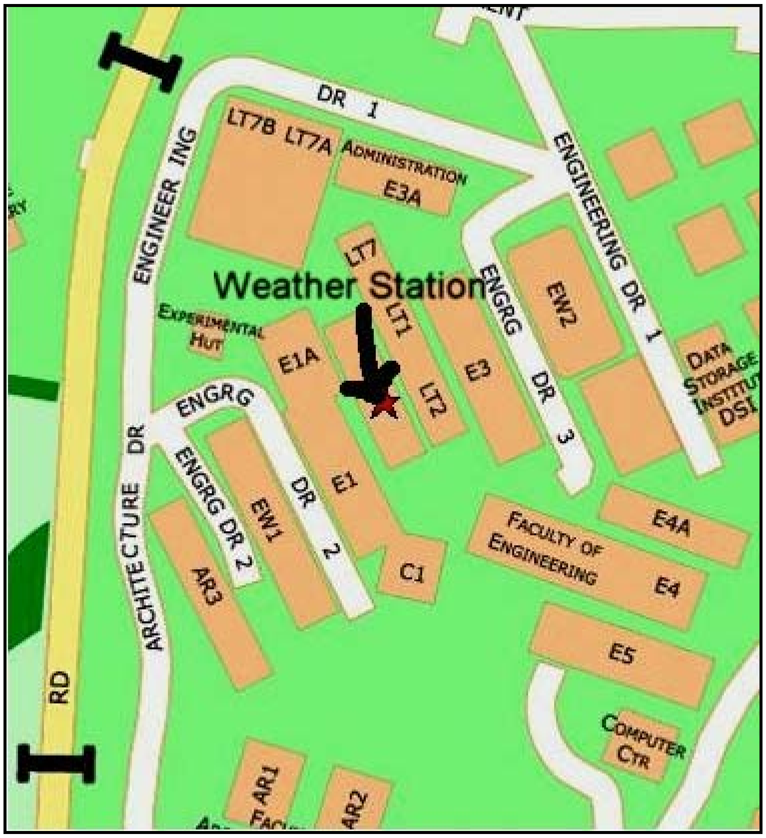

Figure 3-5 Location of Weather Station[3]

Figure 3-5 shows the location of weather station in NUS. It is located very near to the experimental locations.

[3] Site map retrieved and partially edited from Streetdirectory website, Singapore, www.streetdirectory.com, retrieved in 2004

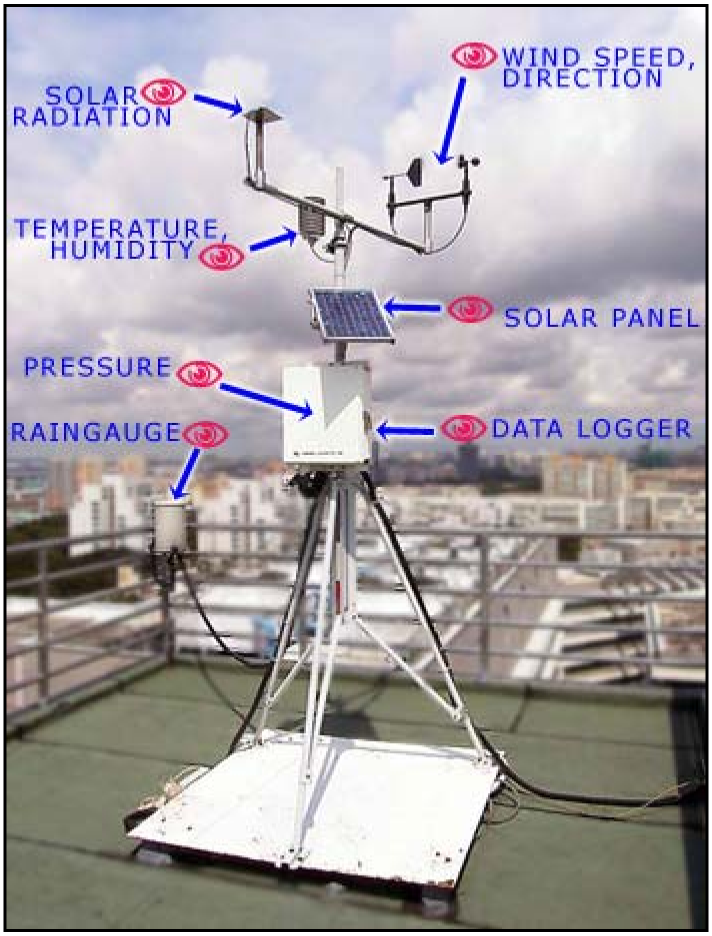

Figure 3-6 Weather Station[4]

Figure 3-6 shows the details of the weather station and Table 3-3 shows the technical specifications of the weather station.

[4] Figure retrieved and reproduced from Department of Geography, National University of Singapore website in 2004; http://courses.nus.edu.sg/course/geomr/front/fresearch/metstation/gallery01.htm

Table 3-3 Specifications of the Weather Station[5]

Variable	Instruments / Operating Principle	Manufacturer (Model)	Units	Accuracy
Pressure	Barometric pressure sensor (Silicon Capacitive Sensor)	Vaisala (PTB101B - CS105)	kPa	+/- 0.2 kPa at 20 degC
Air temperature	T sensor (1000 ohm Platinum Resistance Thermometer)	Vaisala (CS500)	deg C	+/- 0.5 deg C
Relative humidity	RH sensor (Laser-trimmed INTERCAP capacitive chip)	Vaisala (CS500)	% RH	+/- 2.5 % RH
Wind speed	Cup anemometer (Rotation of cup wheel produced ac sine wave proportional to wind speed)	RM Young (wind sentry set 03001)	m/s	+/- 0.5 m/s Threshold: 0.5 m/s
Wind direction	Wind vane (Potentiometer)	RM Young (wind sentry set 03001)	0-360 deg (c.w.)	+/- 5%
Incoming solar radiation	Pyranometer (Silicon photovoltaic detector)	LI-COR (LI-200X)	W/m^2	+/- 3% (typical)
Total Rainfall	Rainguage (Tipping bucket assembly)	Hydrological Services (CS700)	mm/time (5 min or 1 hr)	+/- 2% Resolution: 0.2mm

[5]Information retrieved from Department of Geography, National University of Singapore website in 2004; http://courses.nus.edu.sg/course/geomr/front/fresearch/metstation/info01.htm

3.3.2 Experimental Sites

3.3.2.1 Ayer Rajah Expressway (LOC 1)

It is one of the major expressways in Singapore with a very high traffic volume. Figure 3-7 shows the Ayer Rajah Expressway. The experiment was carried out at LOC 1 as shown in Figure 3-8. The measurement of particulate matter at this site was carried out using Grimm Dust Monitors. One set of dust monitor was used to measure the particle count and the other set of dust monitor was used to measure the particle mass. Temperature and relative humidity were measured using the Hobo meter. These experiments were carried out for a period of five consecutive working days during peak traffic hours (5 pm – 8 pm).

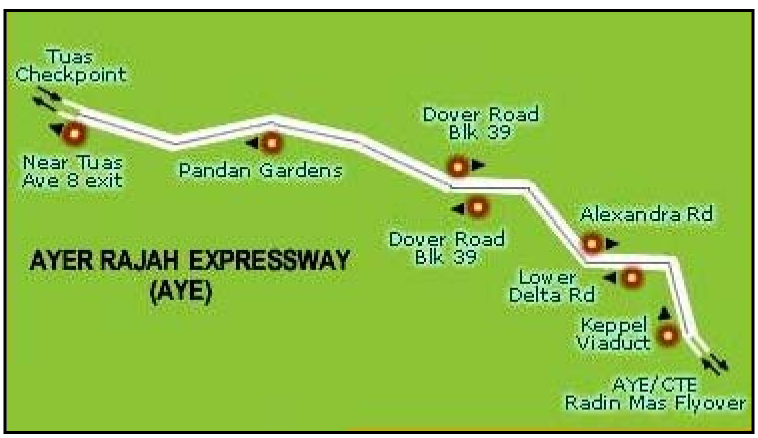

Figure 3-7 Ayer Rajah Expressway[6]

[6] Site Map retrieved and reproduced from website: http://www.onemotoring.com.sg/publish/onemotoring/en/traffic/camera/aye.html ;retrieved in 2004

This set of experiments marked the Phase 1. The expressway (LOC 1) is characterized by a heavy traffic volume. The site was selected at a bus stop to assess the exposure to commuters in the evening between 5 pm and 8 pm. The measurements were carried out at the evening as some preliminary studies revealed traffic jams during those hours.

Figure 3-8 Site layout for LOC 1[7]

[7] Site map retrieved and partially edited from website www.streetdirectory.com, in 2004

3.3.2.2 Clementi Road (LOC 2)

This road is just opposite the School of Design and Environment, National University of Singapore. Figures 3-9 and 3-10 show the site map and sectional view respectively. This is a dual carriage way with two lanes having a low traffic volume in comparison to LOC 1. Experiments were carried out at these locations for two weeks during morning and evening peak traffic hours. The instruments used at these locations were Dust Track, Grimm Dust Monitor and Hobo meter. LOC 2 is used for experiments in Phase 2.

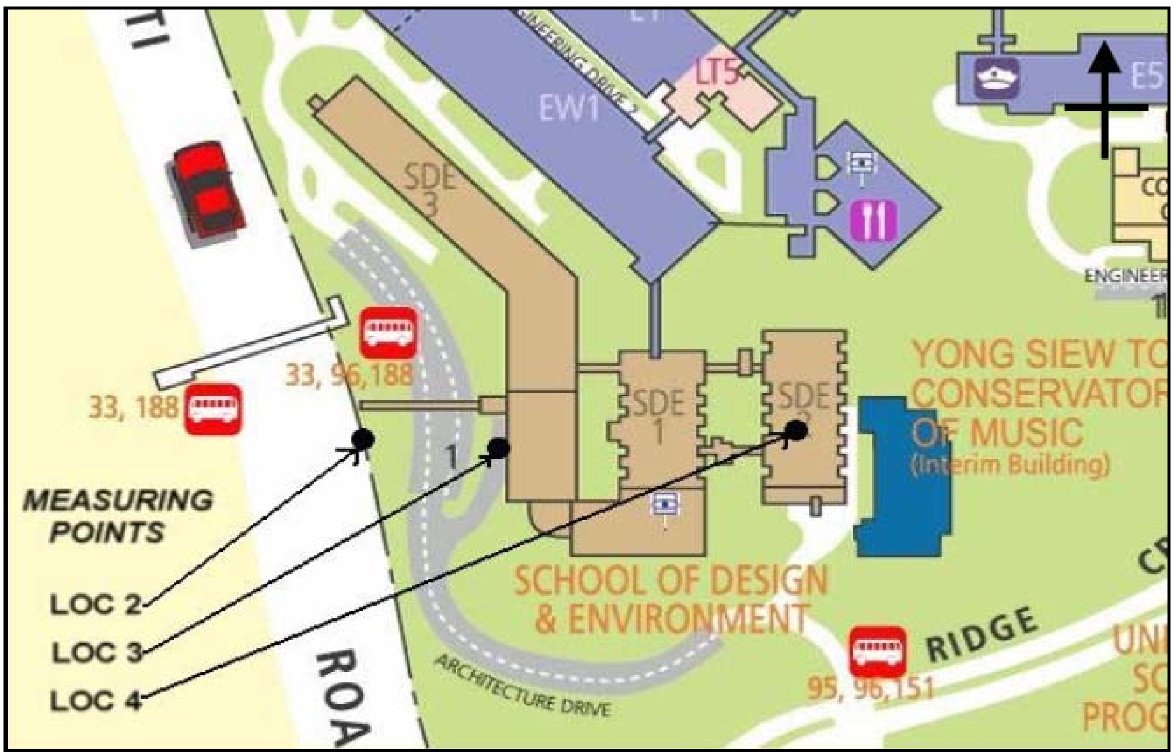

Figure 3-9 Site layouts for LOC 2, LOC 3, and LOC 4[8]

[8] Map extracted and edited from National University of Singapore website in 2004, http://www.nus.edu.sg/campusmap

3.3.2.3 Indoor Naturally-Ventilated Space (LOC 3)

This is a naturally-ventilated location in the School of Design and Environment, National University of Singapore. This location is a sitting area cum lobby space for student's activities. This location is about 60 meters from LOC 2. Measurements were carried out simultaneously at these two locations. The instruments at LOC 3 were Grimm Dust Monitor and Dust Track. The site details and built up orientation is shown in Figures 3-9 and 3-10 respectively. LOC 3 is a partially covered indoor location and is a sitting area for students. LOC 2 and LOC 3 are used for experiments in Phase 2. It is used for studying the migration of particles to indoors.

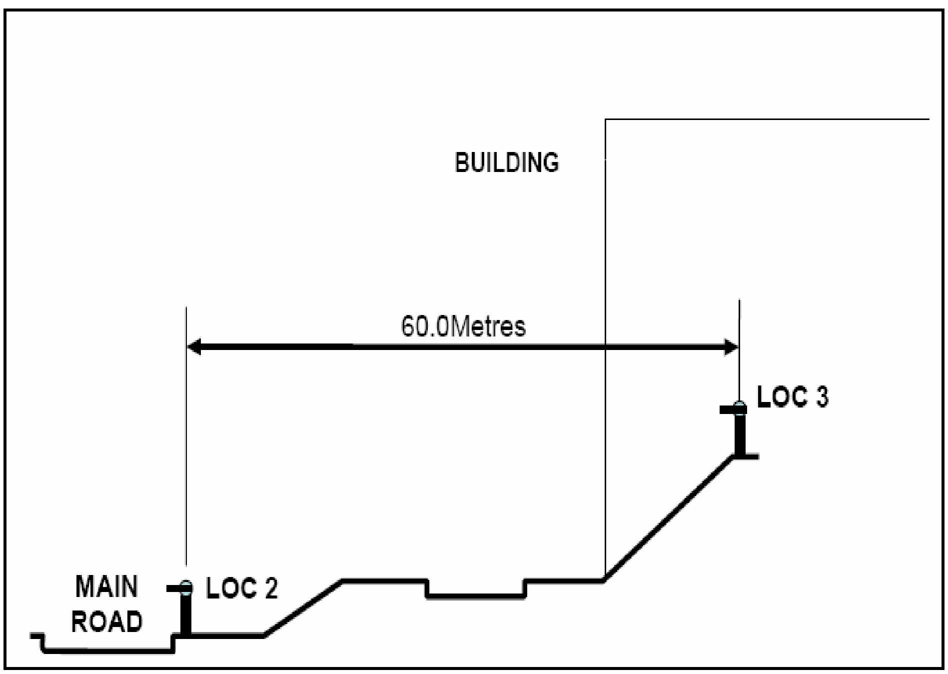

Figure 3-10 Built up section for LOC 2 and LOC 3

3.3.2.4 Indoor Mechanically-Ventilated Space (LOC 4)

This is an office space in the Department of Building, National University of Singapore. This is a non-carpeted space with a single occupant during the measurements.

LOC 3 and LOC 4 are located in the university campus. So comparing locations of different types (NV and MV) was possible.

3.3.2.5 HDB apartments near expressway (LOC 5)

The site is located at the Ayer Rajah Expressway, going towards Jurong. The HDB apartment (residential block) is very close to the expressway. Figure 3-11 shows the site location.

The measurements were carried out at the following locations - bus stop, void deck, level 6 and level 11.The experiment at LOC 5 is to assess the particulate matter at different building heights. This marks Phase 3 of the research work. This study is used to characterize particles at different building heights.

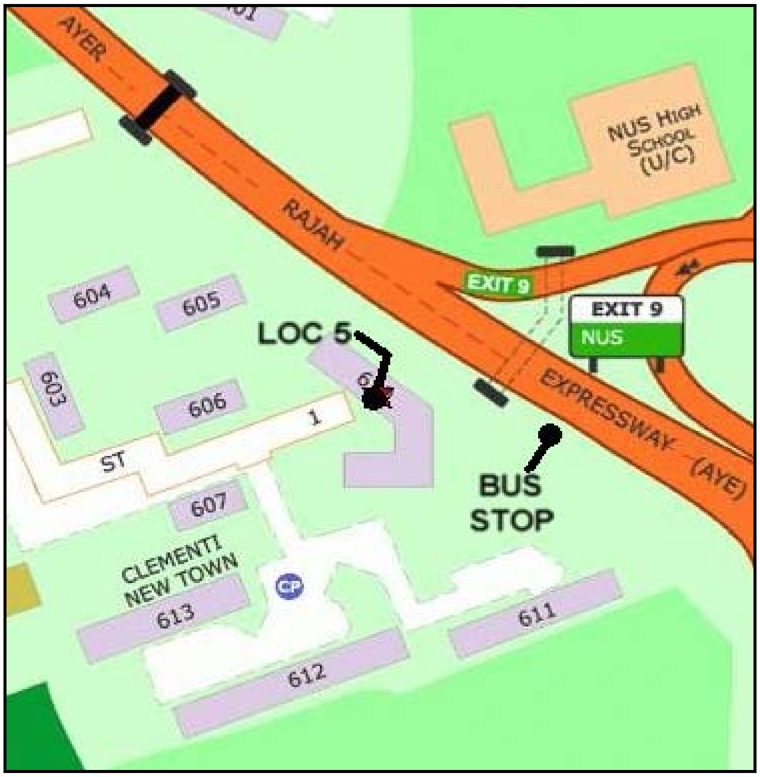

Figure 3-11 Site layout for LOC 5[9]

3.3.3 Data Analysis

The data collected in different phases of work is analyzed using statistical tools. The analysis is based on simple statistics of mean values and standard deviation. Correlation and regression between different variables and different particle constituents are studied. Indoor-Outdoor ratio is calculated to assess the difference between indoor and outdoor locations. Data is presented in forms of tables and graphs to derive meaningful conclusions.

[9] Site map retrieved and partially edited from website www.streetdirectory.com, retrieved in2004

Chapter 4: Characterization of Particles

4.1 Introduction

In this study, experiments were carried out at different indoor and outdoor locations. Gravimetric mass of particulate matter and particle count at different particle sizes were recorded. An attempt has been made to characterize fine and coarse mode particles and differentiate the experimental locations based on these attributes.

4.2 Results and Discussions

4.2.1 Weather Information

In Singapore, the climate is generally hot and humid throughout the year. LOC 1 has a temperature and relative humidity of $31.5 \pm 3.6\ ^{o}C$ and 71.2 ± 13.2 % respectively during the period of measurements. The traffic volume at this location was heavy and wind speed was calm (~ 1 m/s). The temperature and relative humidity at LOC 2 and LOC 3 are $29.6 \pm 2\ ^{o}C$ and 69 ± 10 % respectively. LOC 2 is characterized by low wind speed and traffic volume. The temperature and relative humidity at the mechanically-ventilated space LOC 4 is $22 \pm 0.6^{o}C$ and 65.8 ± 1.7 % respectively. It is important to monitor the ambient weather parameters as fine particles in the accumulation mode have the tendency to coagulate and condense to form particles of larger sizes.

4.2.2 Particle Concentration

Particle concentration was measured both in terms of particle count and particle mass. The observed PM_{10} level at LOC 1, LOC 2, LOC 3 and LOC 4 is 38.8 ± 10.6, 45.0 ± 8.8, 34.7 ± 5.8 and 11.7 ± 0.9 µg/m^3 respectively. Table 4-1 shows the gravimetric characterization of particles at all the experimental locations. It is presented in the form of PM_1, between PM_1 and $PM_{2.5}$ and between $PM_{2.5}$ and PM_{10}. LOC 1 has the highest PM_1 where as LOC 2 and LOC 3 have comparatively more mass fraction between 2.5 and 10 microns. The concentration of PM_1 and $PM_{2.5}$ at Ayer Rajah Expressway (LOC 1) were 60 % and 75 % of PM_{10} respectively. On some minor roads (LOC 2), PM_1 and $PM_{2.5}$ accounted for 45 % and 60 % of PM_{10} respectively. LOC 4 is characterized by negligible mass fraction above 1 micron.

Table 4-1 Characterization of particles gravimetrically (µg/m^3)

Location	**PM_1**	**$PM_{1-2.5}$**	**$PM_{2.5-10}$**
LOC 1	23.9 ± 6.1	4.9 ± 1.1	9.9 ± 4.0
LOC 2	20.2 ± 5.6	7.3 ± 2.0	17.6 ± 5.3
LOC 3	17.5 ± 2.1	4.9 ± 1.3	12.2 ± 3.9
LOC 4	10.5 ± 0.8	0.6 ± 0.1	0.6 ± 0.1

Table 4-2 Characterization on the basis of particle count (count per litre)

Location	PM_1	PM_{1-10}
LOC 1	204104 ± 45940	1025 ± 310
LOC 2	176978 ± 50317	1807 ± 608
LOC 3	164581 ± 22981	1845 ± 358
LOC 4	83273 ± 3189	107 ± 11

Table 4-2 shows the particle characterization in terms of numbers for all the four experimental sites. It is presented in terms of particles less than 1 micron and between 1 to 10 micron sizes. The data shows that fine particles account for 99% of the total particles up to 10 microns. Similar to previous observation in Table 4-1, LOC 1 dominates in the number density of particles less than 1 micron where as LOC 2 and LOC 3 have more particle count between 1 to 10 micron particle sizes. This distribution is elaborated in Figures 4-1 and 4-2.

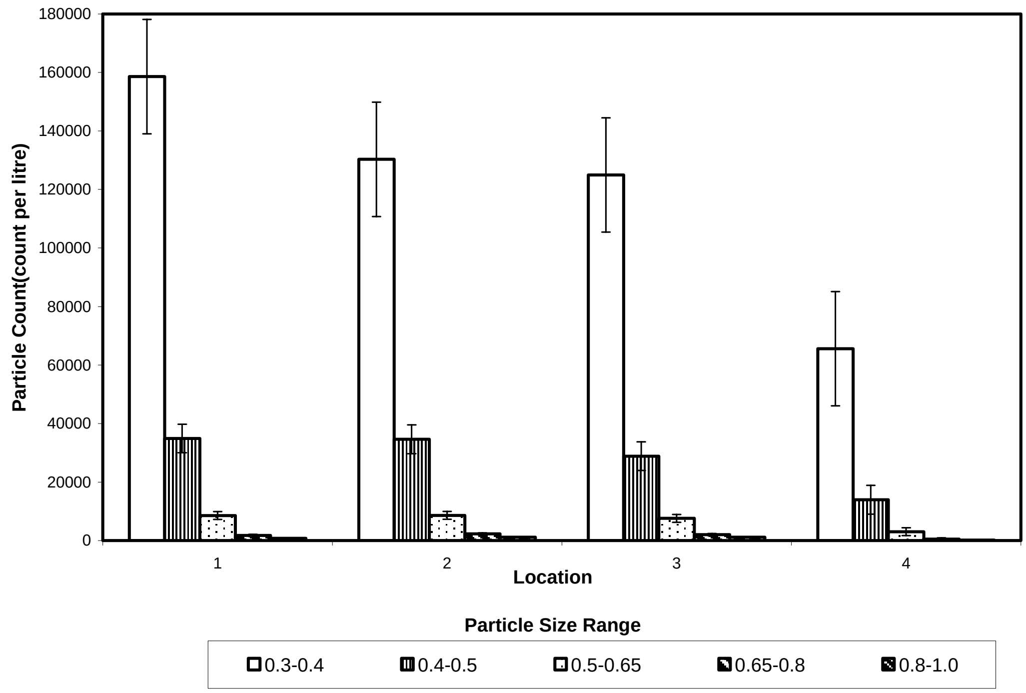

Figure 4-1 Particle Characterization in the region 0.3 – 1.0 micron size

Note: 1, 2, 3 and 4 on x- axis represents LOC 1, LOC 2, LOC 3 and LOC 4 respectively

Figure 4-1 shows the particle distribution in the range of 0.3-0.4, 0.4-0.5, 0.5-0.65, 0.65-0.8, and 0.8-1 at all the four locations on the X – axis and Y- axis representing the particle count.

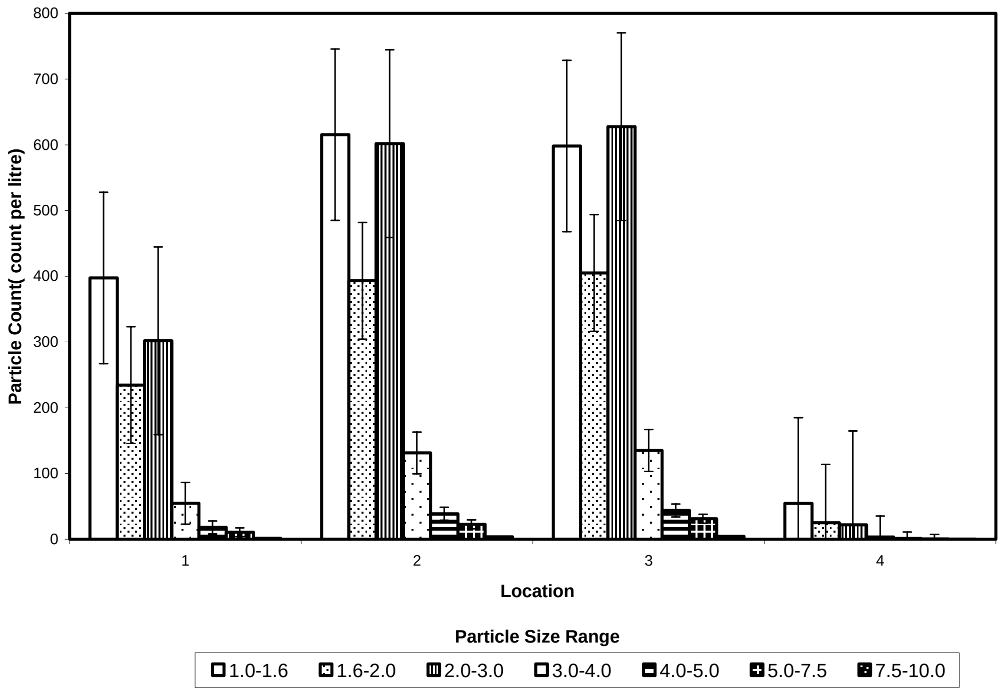

Figure 4-2 Particle Characterization in the region 1.0- 10.0 micron size

Note: 1, 2, 3 and 4 on x- axis represents LOC 1, LOC 2, LOC 3 and LOC 4 respectively

In Figure 4-2, particle size distribution is in the following range: 1.0-1.6; 1.6-2.0; 2.0-3.0; 3.0-4.0; 4.0-5.0; 5.0-7.5; and 7.5 -10 microns.

It is observed that above 0.5-1.0 micron size particle concentration is nearly equal at LOC 1 (11081 ± 2105 count per litre), LOC 2 (12052 ± 1184 count per litre) and LOC 3 (10787 ± 2187 count per litre). Above 1 micron, particle concentration is higher at LOC 2 and LOC 3 as compared to LOC 1. LOC 2 and LOC 3 therefore might represent particles from other sources apart from traffic-related sources. The formation process of fine accumulated particles is mostly combustion, high temperature processes and atmospheric reactions whereas the coarse mode particles are usually formed by mechanical disruption or abrasion. At LOC 1, a heavy traffic volume resulted in larger particle mass due to particles of size less than 1 micron from combustion generated process. The expressway dominates in the finer particles region in the nuclei mode. Coarser particles dominated in naturally-ventilated space and ordinary road with normal traffic volume.

In LOC 4, a mechanically-ventilated space, particles above 1 micron account negligibly in mass. This office space has better air quality in terms of particulate matter. It may owe it to the efficiency of the filtration system at the air handling unit.

4.2.3 Particle Mass Vs Particle Count

PM_{10} was monitored at the indoor and outdoor locations (LOC 2 and LOC 3) during peak traffic hours in the morning and evening. It was observed that the two instruments co-relate reasonably well (R^2 =0.5564, n=60) as shown in Figure 4-3. The values suggest that particle number counts show a significant linear correlation with particle mass for both LOC 2 and LOC 3.

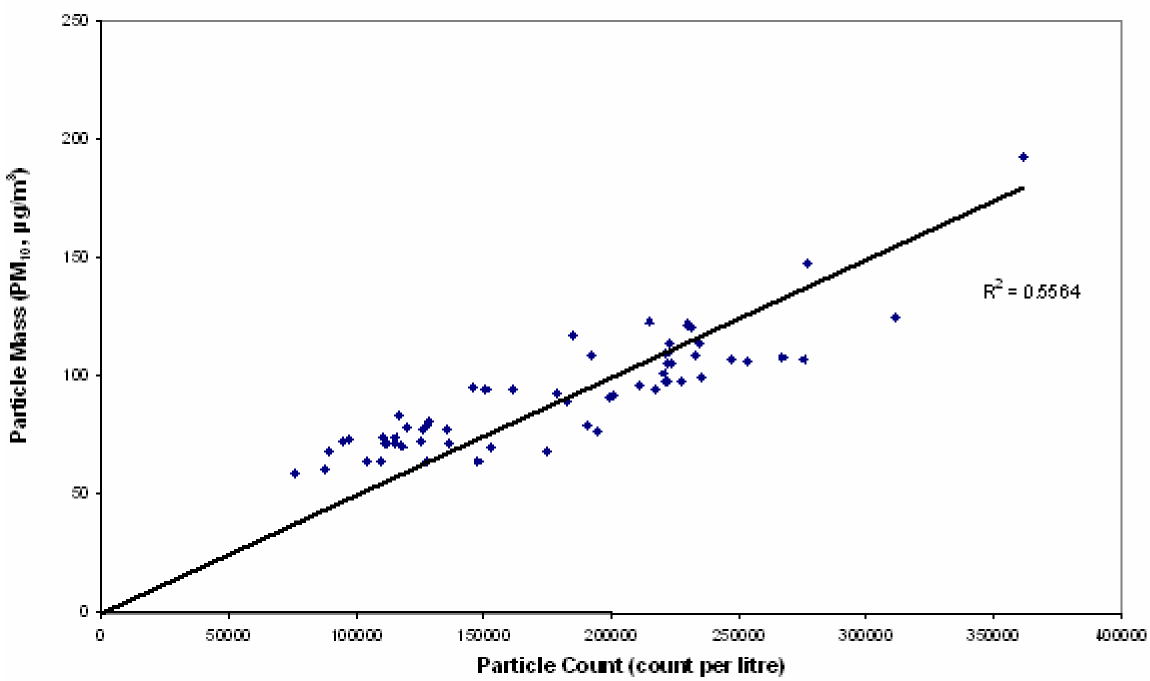

Figure 4-3 Particle Mass (PM_{10}, $\mu g/m^3$) and Particle Count (count per litre) measured using Dust Trak and Grimm Dust Monitor

Table 4-3 shows the coefficient of determination between particle mass and particle count at LOC 2 and LOC 3 during morning and evening periods. **Roy *et al.* (1999)** reported particle count and PM_{10} mass having $r^2 = 0.44$ with n = 44 for a 24 h data at an urban background location. The table shows that the slope is steep for LOC 2 in the morning as compared to LOC 3 but in the evening it is greater for LOC 3. The slope can be a measure of density (function of mass and volume with volume as a function of particle count). It means denser particles at LOC 3 in the evening period. This is supported by the particle count data which shows that in the evening hours; particles between 4–10 micron sizes were more in counts at LOC 3 as compared to LOC 2.

Table 4-3 Coefficient of Determination between Particle Mass and Particle Count

Time	**Statistical Parameter**	**LOC 2**	**LOC 3**
Morning	R^2	0.4872 (n=12)	0.3342 (n=12)
	Slope *(X* 10^{-3}*)*	0.3384	0.2953
Evening	R^2	0.2136 (n=18)	0.7259 (n=18)
	Slope *(X* 10^{-3}*)*	0.2535	0.3793

4.2.4 Fine and Coarse Mode Particles at Outdoor Locations

Table 4-4 shows the correlation of fine and coarse mode particles at the outdoor locations (LOC 1 and LOC 2).

It is observed that better correlation is observed between fine and coarse mode particles at LOC 1 as compared to LOC 2. Even the particle in the nuclei fine mode correlate well with the accumulated fine mode at LOC 1 in comparison to LOC 2. This represents homogeneity of particles at LOC 1 representing to their common source. LOC 2 shows a weak correlation representing the integrated and complex effect of different sources **(WHO, 2002)**. Expressways are characterized by fast moving vehicles, and no other viable sources apart from those transported by wind. Since wind speed is low, therefore transportation of particles from nearby areas is expected to be negligible.

Table 4-4 Correlation between fine and coarse mode particles

LOC 1

	PM_{10}	$PM_{2.5}$	PM_1	$PM_{(2.5\text{-}10)}$	$PM_{(1\text{-}2.5)}$
PM_{10}	1				
$PM_{2.5}$	0.974902	1			
PM_1	0.959185	0.997217	1		
$PM_{(2.5\text{-}10)}$	0.918848	0.807934	0.771266	1	
$PM_{(1\text{-}2.5)}$	0.961814	0.913987	0.881191	0.925747	1

LOC 2

	PM_{10}	$PM_{2.5}$	PM_1	$PM_{(2.5\text{-}10)}$	$PM_{(1\text{-}2.5)}$
PM_{10}	1				
$PM_{2.5}$	0.818993	1			
PM_1	0.631169	0.94872	1		
$PM_{(2.5\text{-}10)}$	0.81577	0.336236	0.079652	1	
$PM_{(1\text{-}2.5)}$	0.850662	0.579718	0.292412	0.811846	1

4.3 Conclusions

The study shows the particle characterization at different locations. It is observed that the PM_{10} levels at LOC 1, LOC 2, LOC 3 and LOC 4 were 38.8 ± 10.6, 45.0 ± 8.8, 34.7 ± 5.8 and 11.7 ± 0.9 µg/m^3 respectively. Despite having higher number density and mass of fine particles, lower PM_{10} was observed at the expressway (LOC 1) as compared to the minor road (LOC 2). Expressway (LOC 1) has higher concentration of fine particles as compared to other locations. Fine particles are mainly generated by combustion processes **(Wilson and Suh, 1997; WHO 2002)**. The fine particles were a result of vehicular combustion as no other source of combustion or fine particles was observed at the expressway during the measurement period. The minor road and the naturally-ventilated spaces (LOC 2 and

LOC 3) have higher concentration of larger size particles. Both these locations showed similar particle distribution. This represents particles of the same characteristics at these two locations. Particle size determines particle behaviour (ageing, transport, deposition) and particle size is closely linked to formation and post formation process **(WHO, 2002)**. The two locations (LOC 2 and LOC 3) were characterized by a number of sources namely; people movement, retarding and accelerating vehicles. This is further supported by a high correlation between fine and coarse mode particles at LOC 1(expressway) as compared to LOC 2 (minor road). The mechanically-ventilated office space (LOC 4) showed a lower particle concentration both in mass and number as compared to all other locations. Particles in the coarse range were nearly absent and this shows the high efficiency of the filtration system. The characterization information can serve as useful criterion for filter selection.

A significant linear correlation is observed between particle mass and particle count. The slope of the curve between mass and count gives an estimate about the density of particles. The particle density can be higher at indoor locations due to larger sources of coarse particles. Density of particle is not a constant value and depends on a number of factors including the sources and the ambient climate. Aerosol particles, mainly water soluble change their size as a function of the humidity of air **(Ferron, 1977).** A higher humidity which is a characteristic of Singapore’s climate can therefore play a crucial role in modifying the primary particles, hence affecting the density.

The importance of particle count is also realized and research is being conducted globally to gather more information about the particles. The present study shows that fine particles comprise 99 % of the particle count. These fine particles can have severe health implications as they penetrate deep into the respiratory system. Guidelines and standards for particles for good indoor quality should therefore be based on particle count rather than solely on particle mass because it gives better information about the pollutant. Studies have shown that particle count is more closely associated with health effects. Auditing of buildings is around to serve as preventive measures for building related illnesses.

Chapter 5: Indoor-Outdoor (I/O) Ratio and Effect of Ambient Environment on I/O

5.1 Introduction

This chapter investigates the migration of particles to indoor spaces. Ambient environment can play a crucial role in governing the migration of air pollutants like particles. This chapter further investigates the role of factors like wind speed, temperature and relative humidity in the migration of particles. It also compares the Indoor-Outdoor ratios of naturally-ventilated and mechanically-ventilated spaces.

5.2 Methodology

A building located in a local university is selected as the indoor location and the nearby bus stop is selected as an outdoor location. The monitoring was carried out during the peak period in the morning and evening hours (8 am–11 am and 5 pm-8 pm). Figures 5-1 and 5-2 show the experimental set up at the two locations.

The migration is investigated by determining Indoor-Outdoor ratios (I/O). I/O ratio for naturally-ventilated space is then compared with mechanically-ventilated office space located in the same building.

The effect of ambient environment on I/O ratio is studied using Pearson's Correlation and by plotting I/O ratio with respect to various ambient parameter's (temperature, relative humidity and wind speed).

Figure 5-1 Experimental set up at outdoor location (LOC 2)

Figure 5-2 Experimental set up at indoor location (LOC 3)

5.3 Results and Discussions

5.3.1 Indoor–Outdoor (I/O) Ratio

The Indoor-Outdoor Ratio (I/O) for PM_{10} for LOC 3 (indoor naturally-ventilated) and LOC 2 (outdoor space) is 0.91 as compared to LOC 4 (mechanically-ventilated) and LOC 2 of 0.46. Figure 5-3 shows the I/O ratio for different range of sizes of particles in naturally-ventilated and mechanically-ventilated spaces. It is observed that the I/O ratio for mechanically-ventilated space is mostly between 0.2 and 0.5 for particles up to 0.8 microns and less than 0.1 for higher size particles. In naturally-ventilated spaces, the I/O ratio varied from 0.8-1.0 for particles less than 4 microns and greater than unity is observed for size larger than 4 microns. The particles in the fine mode are generally formed by combustion processes. The increase in I/O ratio above 4 micron may be attributed to the presence of people. The particles in the coarse range (2.5 µm and above) are normally formed by mechanical disruption (crushing, grinding, abrasion of surfaces), suspension of dust and reaction of gases in or on particles. It is found that there is a continuous decline in I/O with increasing size range in the mechanically-ventilated space whereas no definite trend in the case of naturally-ventilated space. This shows the complexity involved with naturally-ventilated spaces and highlights the difficulty involved in predicting the concentration of particles. The reduction in I/O ratio for larger size particles is due to the filtration system of mechanically-ventilated system.

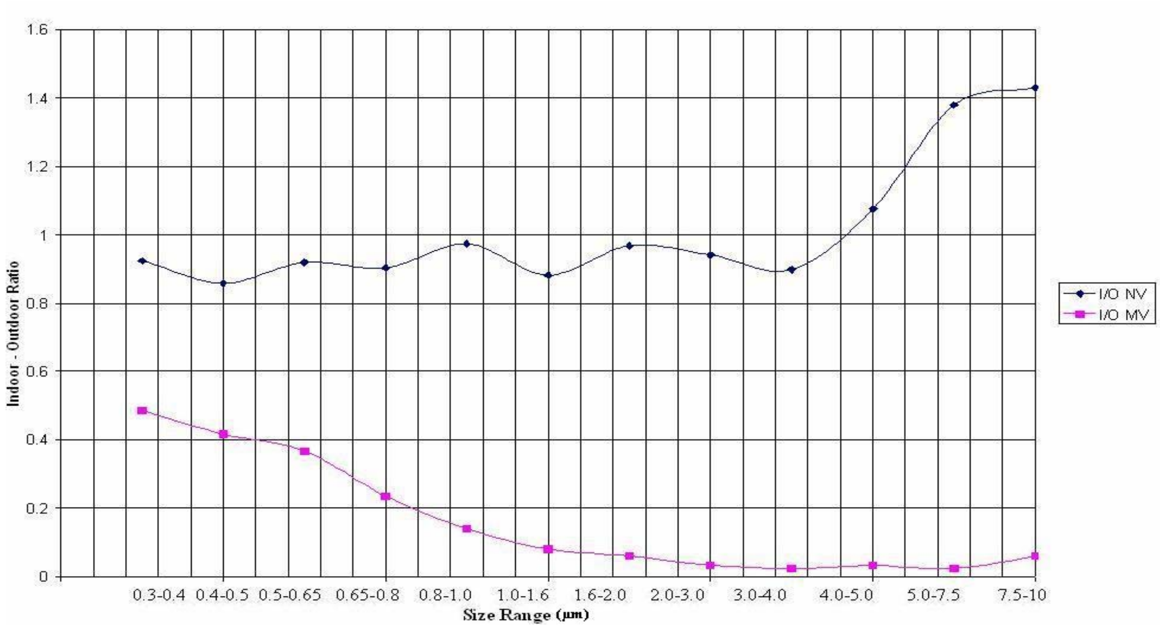

Figure 5-3 Variation of I/O ratio with size range at naturally and mechanically - ventilated spaces

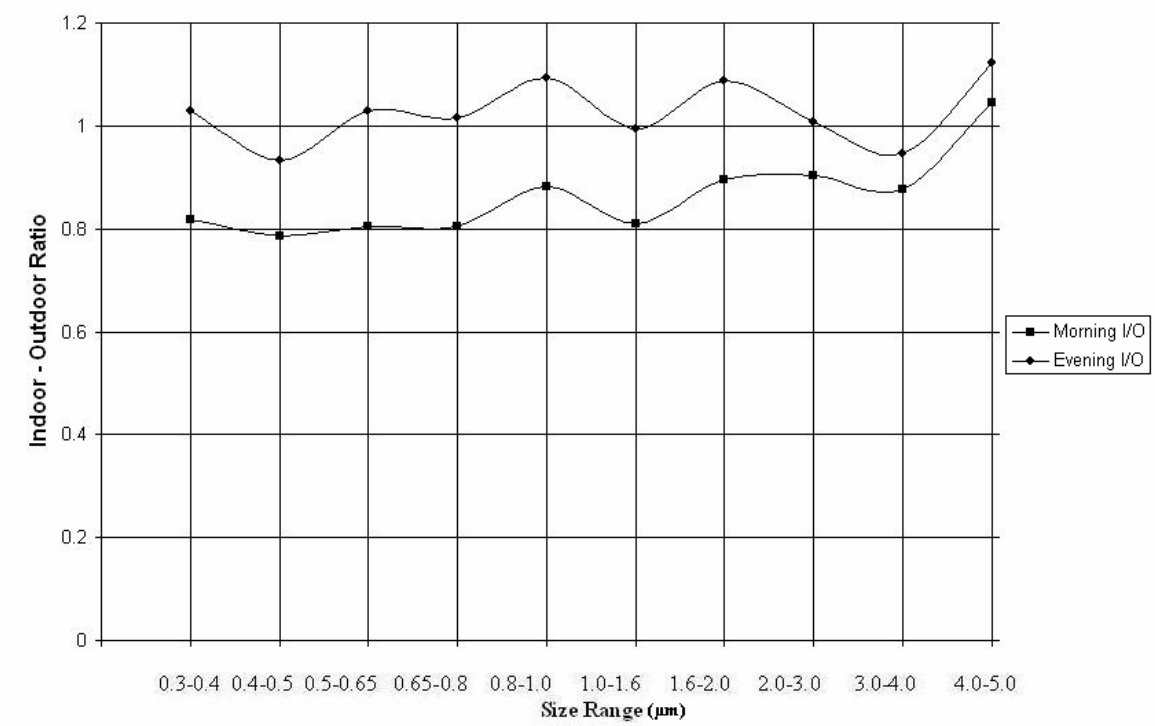

Figure 5-4 Indoor–Outdoor ratio (I/O) at LOC 2 during morning and evening peak traffic hours

Figure 5-4 shows the Indoor-Outdoor ratio at the morning and evening peak-traffic hours between LOC 2 and LOC 3. It is observed that the I/O ratio is higher in the evening as compared to morning hours. This higher indoor concentration could be due to more indoor activities in the evening. It could also be due to the difference in ambient climatic condition between the morning and evening times. It was observed that evenings were characterized by high temperature and lower relative humidity which can possibly increase the migration of particles to the indoor locations.

5.3.2 Effect of Ambient Environment on Indoor–Outdoor Ratio of Particles

The factors affecting the migration of particles can mainly be the source concentration, ambient temperature, relative humidity, wind speed, wind direction, terrain and infiltration characteristics of the envelope. In this chapter the focus is on the ambient condition which cannot be controlled by human design whilst other factors can be controlled. The possible approach is to have a detailed study on these parameters and develop proper design to minimize the transgress.

Factors like wind speed, wind direction, temperature and humidity can play an important role in the migration of such fine particles as discussed below.

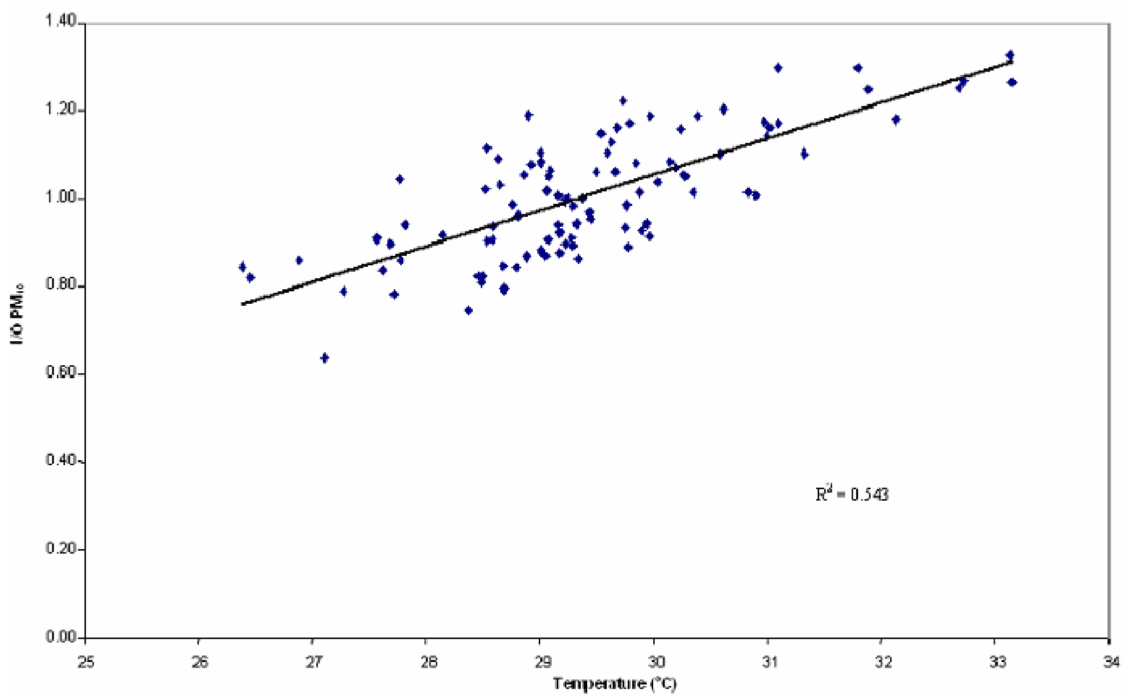

Figure 5-5 Variation of I/O PM_{10} with Temperature

Figure 5-5 shows the variation of I/O PM_{10} with the ambient temperature. There is a strong correlation between I/O PM_{10} and ambient temperature. It is observed that with increase in ambient temperature there is an increase in I/O ratio which implies more particles migrating indoors. This may be attributed to the temperature gradient that is established between the indoor and outdoor locations which favors the motion of the particles.

Figure 5-6 shows the variation of I/O PM_{10} with ambient relative humidity. It shows that with increase in ambient RH, there is decrease in I/O. This implies less migration of particles which may be due to the possibility of increase in particle size with relative humidity.

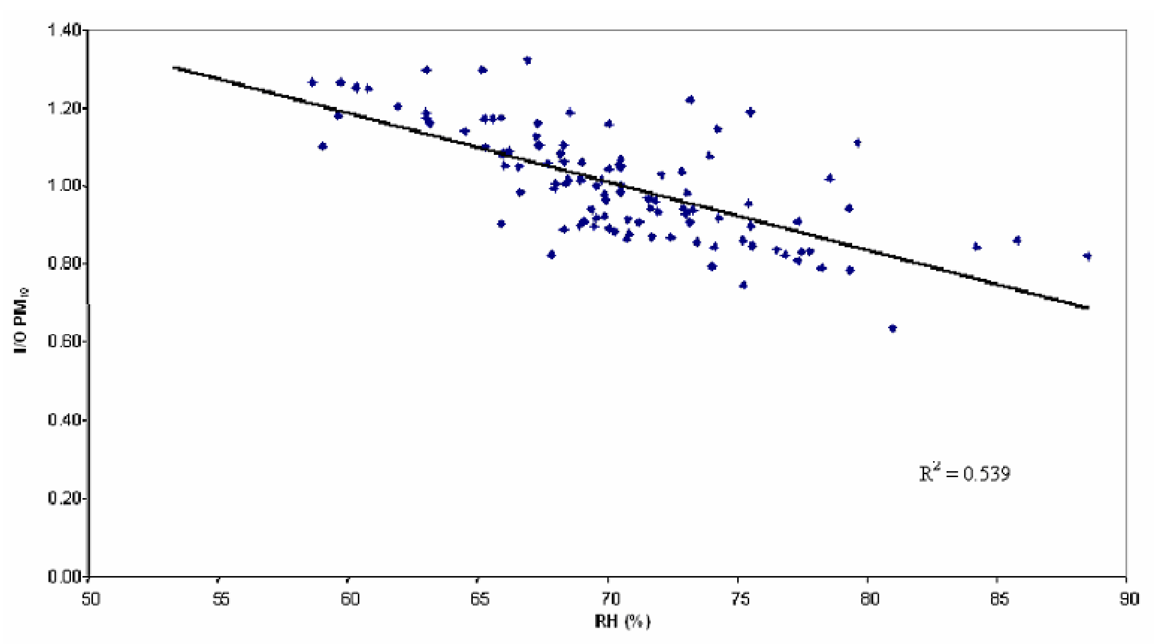

Figure 5-6 Variation of I/O PM_{10} with RH

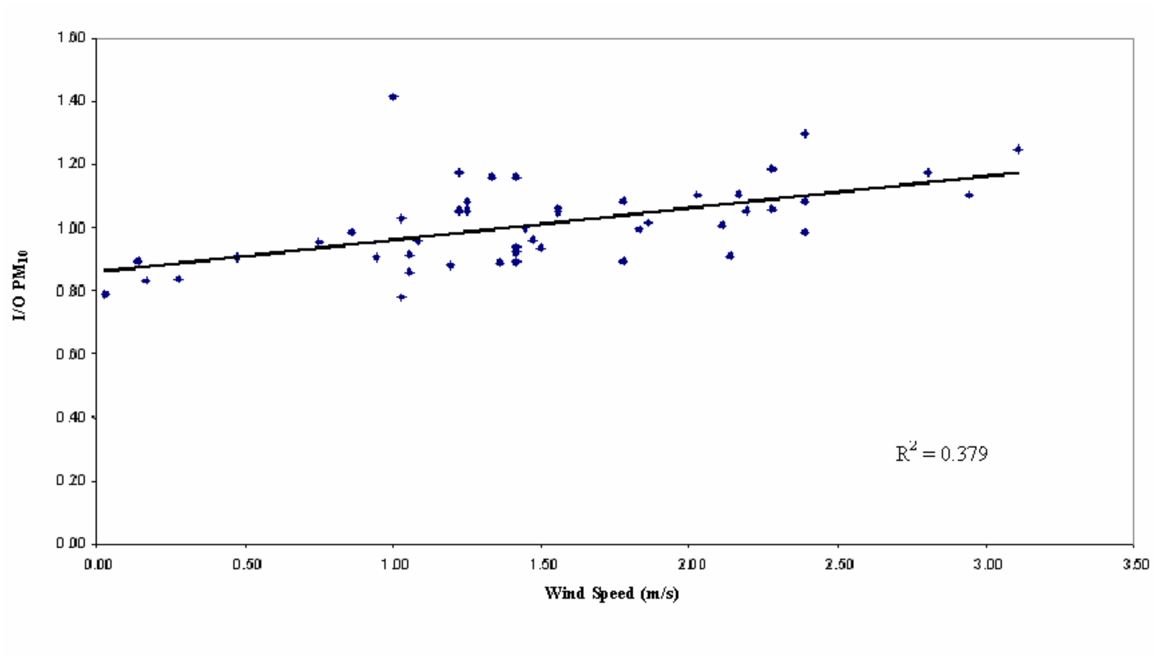

Figure 5-7 Variation of I/O PM_{10} with Wind Speed

Figure 5-7 shows the variation of wind speed with I/O PM_{10}. An increase in wind speed shows an increase in I/O as more particles are migrating indoors.

Table 5.1 summarizes the results of regression analysis between I/O and ambient environmental parameters. From the table it can be concluded that temperature plays the most significant role in affecting the I/O ratio followed by relative humidity and wind speed. **Cuhadaroglu and Demirci (1997)** investigated the influence of some meteorological factors on particle concentration in Turkey and gave the following regression equation ($R^2 = 0.56$).

[Particle Concentration] = 168.71 + 7.613 x [Temperature] – 1.809 x [Relative Humidity].

The above equation estimates particle concentration in Trabazon city in Turkey and shows that suspended particle concentration increased with increasing temperature and decreasing humidity. In the present research in Singapore, analysis, show that I/O is increased with increasing temperature and wind speed. The I/O decreases with an increase in relative humidity.

Table 5-1 Results of regression analysis

S.No.	Independent Variable	Dependent Variable	R^2	Regression Equation	Sig.	Remarks
1	Temperature (T)	I/O	0.543	-1.652 + 0.09T	p<0.05	Statistically significant
2	Relative Humidity (RH)	I/O	0.539	2.559 - 0.02RH	p<0.05	Statistically significant
3	Wind Speed (WS)	I/O	0.379	0.841 + 0.112WS	p<0.05	R^2 weak
4	T, RH	I/O	0.563	0.348 + 0.05T - 0.01RH	p<0.05	Slight change in R^2 in comparison to S. No. 1 & 2. This shows T and RH are also inter-related.
5	T, WS	I/O	0.557	-1.251 + 0.08 T + 0.03WS	p<0.05	Slight change in R^2 in comparison to S. No. 1
6	RH, WS	I/O	0.540	2.458 – 0.02 RH + 0.009 WS	p<0.05	Slight change in R^2 in comparison to S.No. 2
7	T, RH, WS	I/O	0.566	0.115 + 0.05T - 0.009RH + 0.01WS	p<0.05	Very Slight Change in R^2 in comparison to S.No 4 after including Wind speed as variable

Table 5-1 showed that the coefficient of determination didn't increase significantly after incorporating the combined effect of relative humidity or wind speed as these environmental parameter are also strongly correlated as shown in Table 5-2.

Table 5-2 Pearson Correlation between Temperature, Relative Humidity and Wind Speed

	Temperature	**Relative Humidity**	**Wind Speed**
Temperature	1.000	-0.921	0.726
Relative Humidity	-0.921	1.000	-0.815
Wind Speed	0.726	-0.815	1.000

Table 5-3 shows Pearson Correlation of I/O of different particle sizes with temperature, relative humidity and wind speed. It is observed that with increase in size the dependence of I/O on these ambient parameter decreases. These ambient parameters are governing in the case of fine particles where Brownian motion and diffusion may be more dominant. Result shows that for fine particles temperature may be more crucial than wind speed in governing the migration. The correlation of wind speed is almost constant with particle size as usually the diurnal variation of wind speed is not as strong as that of other meteorological parameters (e.g. temperature and relative humidity). Whilst wind just serves as a carrier, parameters like temperature and humidity can lead to physical and chemical nature of the particles and which will finally affect the migration. The negative correlation with relative humidity is perhaps because of the fact that the particles are undergoing wet deposition under high humidity and rainy conditions. This negative correlation is smaller for larger particles, which may mean that these are not removed as efficiently as the small particles. The particle behavior below 0.3 micron can not be predicted using the present study due to instrumental limitations. It is observed that above 1 micron size the effect of temperature is comparatively reduced as compared to particle below 1 micron. Particles less than 1 micron are in the nuclei and accumulation mode and environmental factors such as temperature and humidity plays a more significant role.

Table 5-3 Pearson Correlation of I/O of different particle sizes with ambient parameters

Particle Size (micron)	Pearson's Correlation		
	Temp. (^{o}C)	RH (%)	Wind Speed (m/sec)
0.3 -0.4	0.685	-0.512	0.616
0.4-0.5	0.726	-0.501	0.621
0.5-0.65	0.710	-0.499	0.617
0.65-0.8	0.588	-0.420	0.644
0.8-1.0	0.359	-0.266	0.608
1.0-1.6	0.330	-0.306	0.655
1.6-2.0	0.165	-0.231	0.623

5.4 Conclusions

The I/O ratio for mechanically-ventilated space is much lower than the naturally-ventilated space. Particles above 2.5 micron size are nearly absent in mechanically-ventilated spaces. This is due to the filtration system used in the supply of air to the conditioned spaces. It is interesting to observe that there is variation in I/O for naturally-ventilated buildings in the morning and evening periods. This may mainly be attributed to the increased level of indoor activity or higher temperature and lower humidity which favors the transgress of particles.

This study clearly shows that the ambient parameters like temperature, relative humidity and wind speed can effect the migration of particulate matter to indoor location.

- Wind speed and temperature have a positive influence on migration of particulate matter.
- Relative humidity has a negative influence on the transport phenomenon of particulate matter.
- Temperature may be a dominant factor governing the migration of fine particles as compared to wind speed.
- With the increase in size of particle their dependence on ambient parameters comparatively decreases more for temperature and relative humidity as compared to wind speed.

5.5 Limitations

There are a few limitations to this study. As stated that particles is a complex entity and has a number of sources. It may be argued that there might be presence of indoor sources. The presence of indoor sources will affect the I/O ratio and migration of particles from outdoor environment to indoor environment cannot be predicted accurately. This can be well determined only by chemical test and source apportionment techniques by using markers. The different particle sources will have particles having different physical and chemical characteristics. These particles will also differ in densities and the different chemical constituents will have different affinity to parameters like temperature and relative humidity. This will also affect particle interaction processes like coagulation and condensation. Hence a chemical analysis of the samples will reveal useful information on the nature of particles and the possible transformations. However, these were not carried out owing to lack of required facilities for such studies.

Chapter 6: Particle Distribution at different heights in a Residential Building

6.1 Introduction

Variation in concentration of particles at a given height depends on several factors, which include vehicle generated turbulence, variation in traffic flow, meteorological parameter and geometry of street. In this study, vertical profile of particulate matter was measured in a building located close to an expressway.

6.2 Methodology

A residential building of 12 storeys (LOC 5) located very close to an expressway is selected. This building is a naturally-ventilated apartment and located in proximity to the expressway (10 metres from the shoulder of expressway).

The measurements were carried out at the following locations for a period of 15 consecutive days during 5 pm – 8 pm in the evening.

- Bus stop

- Void deck - Deck refers to the ground storey. This storey houses the common facilities for the residents of the building , e.g. letterboxes, public phone, round tables and benches (as shown in Figure 6-2)
- Level 6- Level 6 refers to storey 6 and represents intermediate building height. The instruments were placed at the parapet wall of the common corridor, 17 m above ground level. The corridor is 2.64 m wide.
- Level 11 – Level 11 refers to storey 11. The instruments were placed at the parapet wall of the common corridor, 31 m above ground level

There is a light cover of trees between the expressway and the building. The tree cover extends till the intermediate building height (Level 6) as shown in Figure 6-1. Figure 6-2 shows the experimental set up at the deck. Apart from the tree cover no other significant obstructions were present. Figure 6-3 shows the site conditions of the nearest bus stop at which the measurements were taken and Figure 6-4 shows the experimental set up at the bus stop. Figures 6-5 shows the sectional view of the corridor in building.

Particle concentration has been measured both in term of mass (μg/m^3) and number density using Grimm Dust Monitor described in the previous chapters.

Figure 6-1 Photograph of Building Block

Figure 6-2 Experimental Set up inside the Deck

Figure 6-3 Photograph of the Bus stop

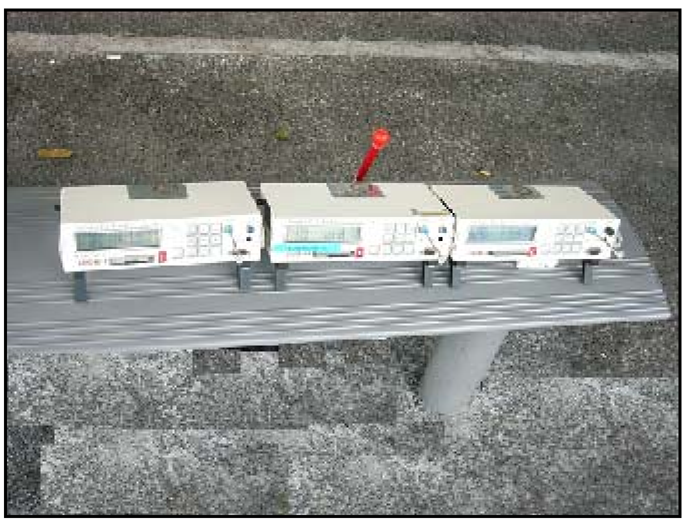

Figure 6-4 Experimental setup at the Bus stop

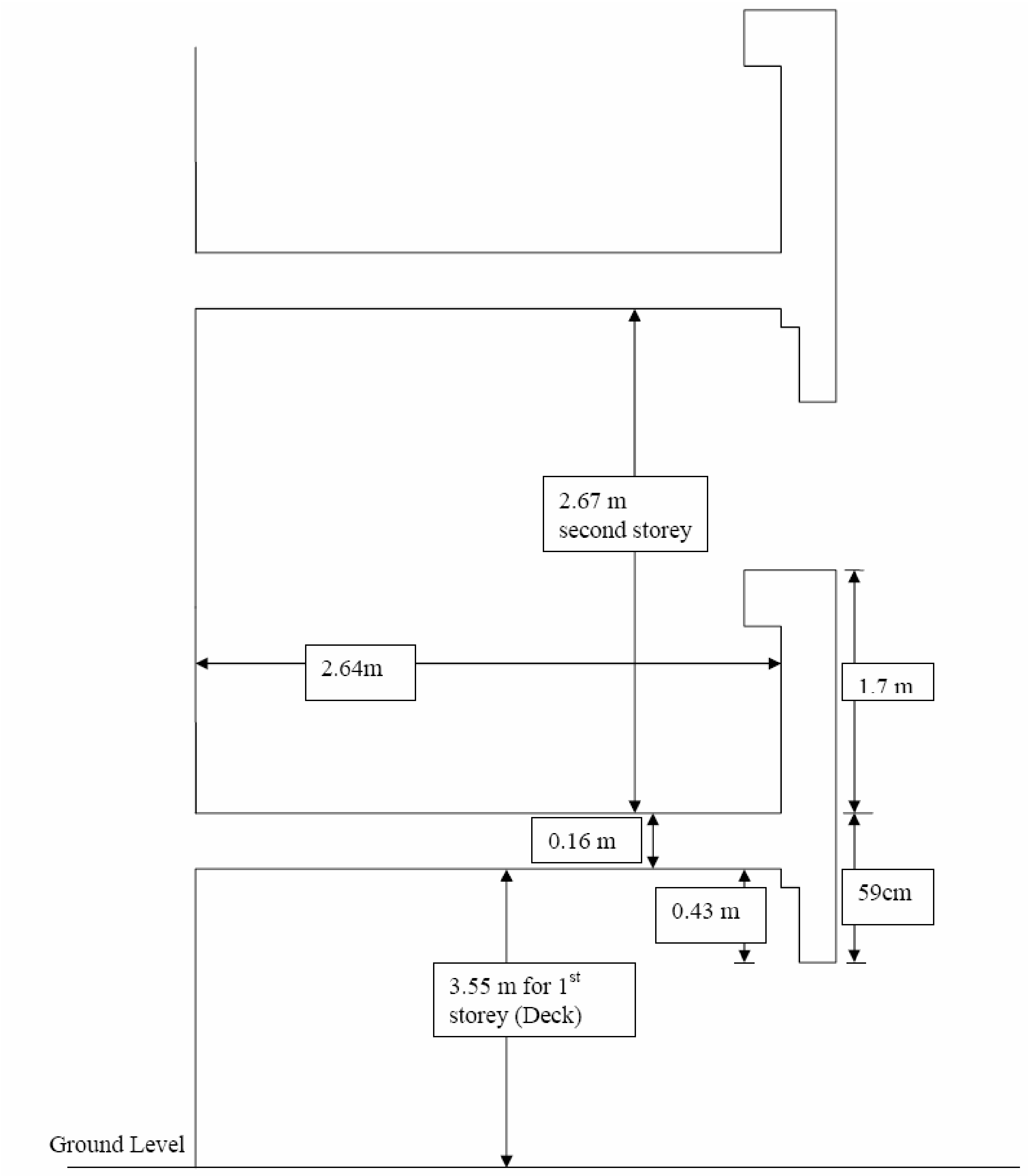

Figure 6-5 Sectional details of the corridor in Building

6.3 Results and Discussions

6.3.1 Particle characterization at different building heights

The study of particle concentration in a naturally-ventilated residential building along a major expressway having a high traffic volume revealed some interesting facts. The variation in concentration at different building heights is governed by many factors which will be discussed in detail in the following sections.

Figure 6-6 shows the mass distribution measured in terms of $PM_{1,}$ $PM_{2.5}$ and PM_{10} measured at deck, level 6, level 11, and bus stop averaged over the complete measurement period. It could be observed that at all the four locations have nearly the same average PM_1 whereas there is a considerable difference in PM_{10} concentrations. This may imply that PM_1 (fine particles) has the ability to travel to long distances and are not that much affected by gravitational settling. Level 6 dominates in terms of PM_{10} while bus stop is having the least PM_{10} It could be seen that there is a small difference in $PM_{2.5}$ concentration while there is a considerable difference in PM_{10} at different measuring points. Level 6 has a slightly higher PM_{10} as compared to level 11. The deck is having the lowest PM_1 but a comparatively higher PM_{10} as compared to bus stop.

The concentration of PM_1 is nearly the same at the different measurement points (Figure 6-6). However there is a difference in concentration of PM_{10} at the four measuring points. This implies that the particles between 1–10 micron sizes are making this difference. Table 6-1 further illustrates the different components of particulate matter taken as a ratio of PM_{10}.

The table shows that bus stop has the highest proportion of PM_1 out of PM_{10} as compared to the other measuring points, namely deck, level 6 and level 11. The gravimetric component between 1–2.5 particle sizes is maximum at the deck and minimum at the bus stop. The gravimetric component between 2.5-10 particle sizes is maximum at the intermediate building height (level 6) where as the bus stop is having the least. This shows that the coarse mode particles are held in suspension at the intermediate building height. The deck shows the highest concentration of particles between1–2.5 µm as these particles are washed out more effectively from higher building heights to lower building heights as compared to compared to bigger size particles. The bus stop shows a higher PM_1/PM_{10} which shows that it has mostly combustion generated particles from the vehicular traffic on the expressway.

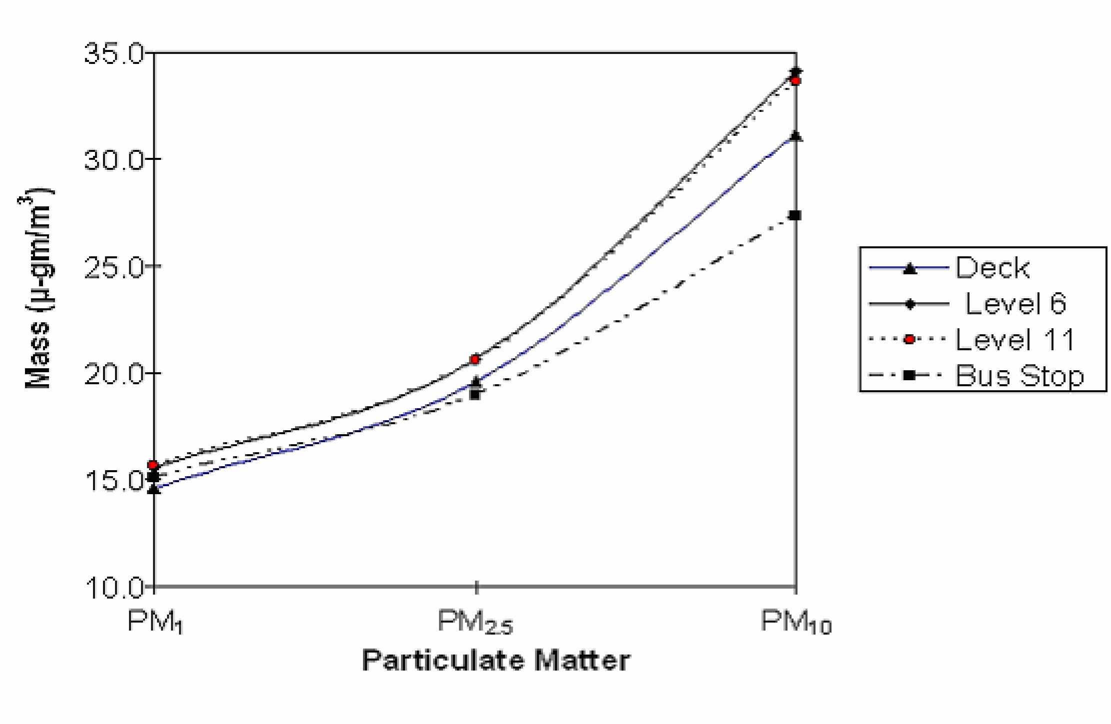

Figure 6-6 Mass Distribution at different points

Table 6-1 Constituents of Particles

Location	PM_1/PM_{10}	$PM_{1-2.5}/PM_{10}$	$PM_{2.5-10}/PM_{10}$
Deck	0.47	0.16	0.37
Level 6	0.45	0.15	0.40
Level 11	0.46	0.15	0.39
Bus stop	0.55	0.14	0.31

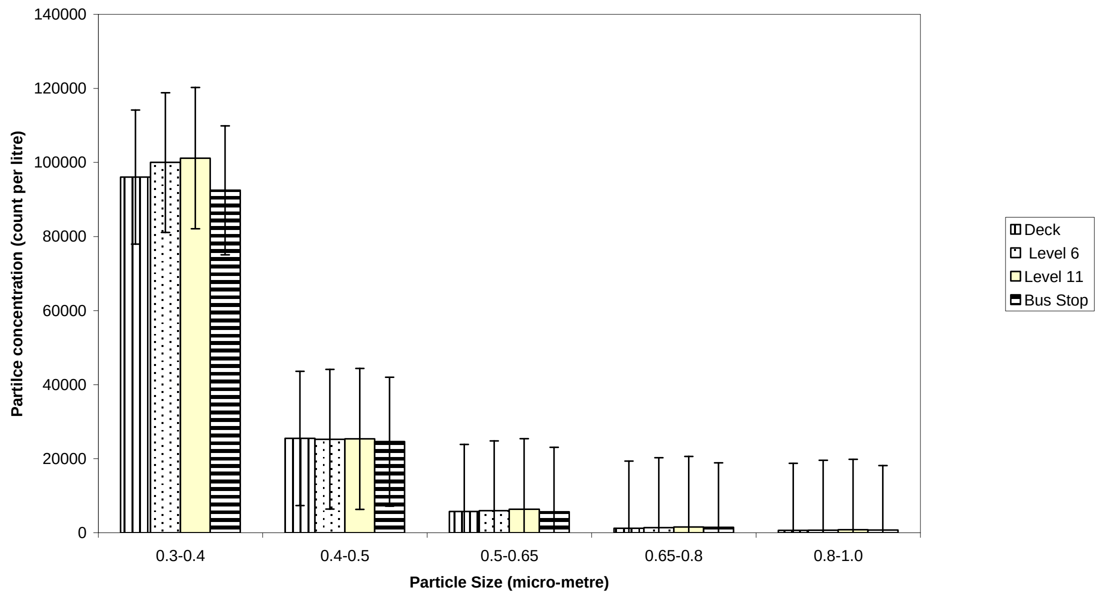

Figure 6-7(a) Particle Characterization at Bus stop, Deck, Level 6 and Level 11

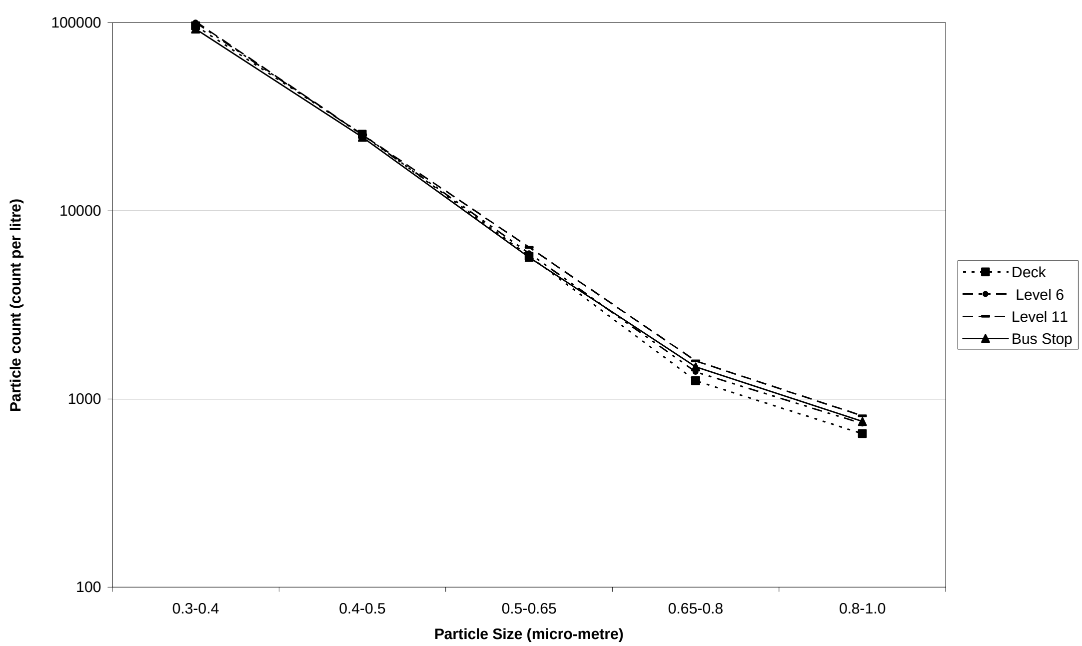

Figure6-7(b) Particle Characterization at Bus stop, Deck, Level 6 and Level 11

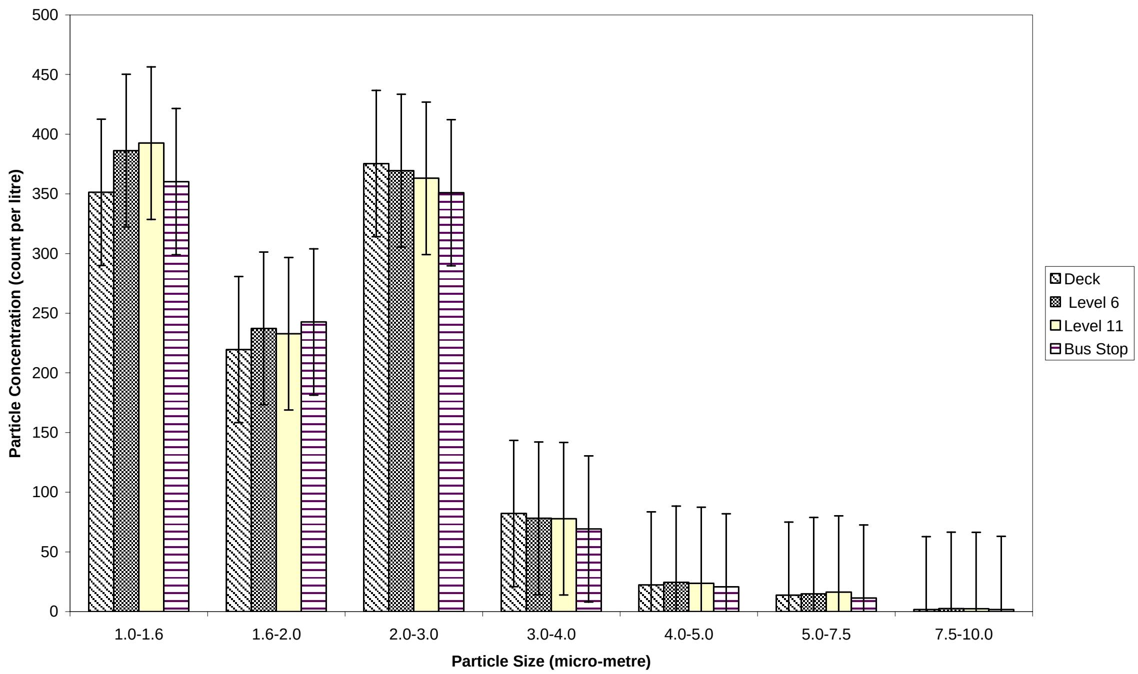

Figure 6-8 (a) Particle Characterization at Bus stop, Deck, Level 6 and Level 11

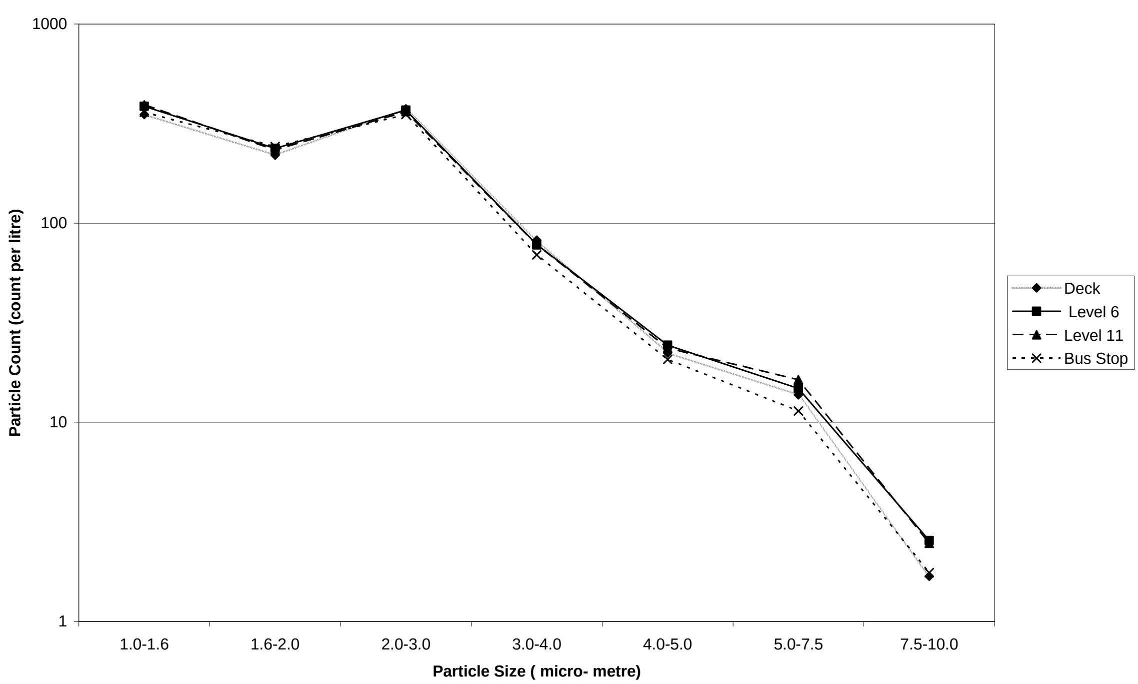

Figure 6-8 (b) Particle Characterization at Bus stop, Deck, Level 6 and Level 11

Figures 6-7(a, b) and 6-8(a, b) show that the particle number distribution at different measuring points. The X- axis shows the particle size where as the Y- axis shows the particle count (counts per litre). In Figures 6-7(b) and 6-8(b), the particle concentrations were plotted on the log scale. Figure 6-7(a, b) shows the particle distribution from 0.3 -1 micron particle size. Level 6 forms the uppermost curve while the deck forms the lower most curve. Figures 6-8(a, b) show the particle distribution from 1 micron size particles to 10 micron size particles. Bus stop has the least concentration. It is observed that all the measuring points follow the same trend. For smaller sizes particles the difference in concentration at the experimental locations is marginal but becomes significant at bigger sizes.

Table 6-2 shows the coefficient of determination between particle mass and particle count at the four measuring points. The slope of the curve between particle mass and particle count represents the mass of particle per unit particle count. For PM_1 it is observed that the slope is highest for the bus stop. The deck has the highest slope for $PM_{1\text{-}2.5}$, and level 6 has the highest slope for particles between 2.5–10 micron sizes. This shows that different particle component dominates at different building heights in a multi-storey building. Hence a composite characterization in terms of PM_{10} may not reveal the actual dominant phase of particles. Similar results have been presented in Table 6-1. This information on distribution also helps to present the relationship between fine and coarse particles. This will be discussed in the subsequent tables.

Table 6-2 Particle Mass vs. Particle Count

Location	Statistical Parameter	PM_1	$PM_{1-2.5}$	$PM_{2.5-10}$
Deck	R^2	0.9491	0.9263	0.6725
	Slope	0.0001	0.0064	0.0360
Level 6	R^2	0.9260	0.9282	0.4468
	Slope	0.0001	0.0062	0.0422
Level 11	R^2	0.9618	0.8060	0.4035
	Slope	0.0001	0.0061	0.0413
Bus Stop	R^2	0.9065	0.1144	0.1075
	Slope	0.0002	0.0049	0.0299

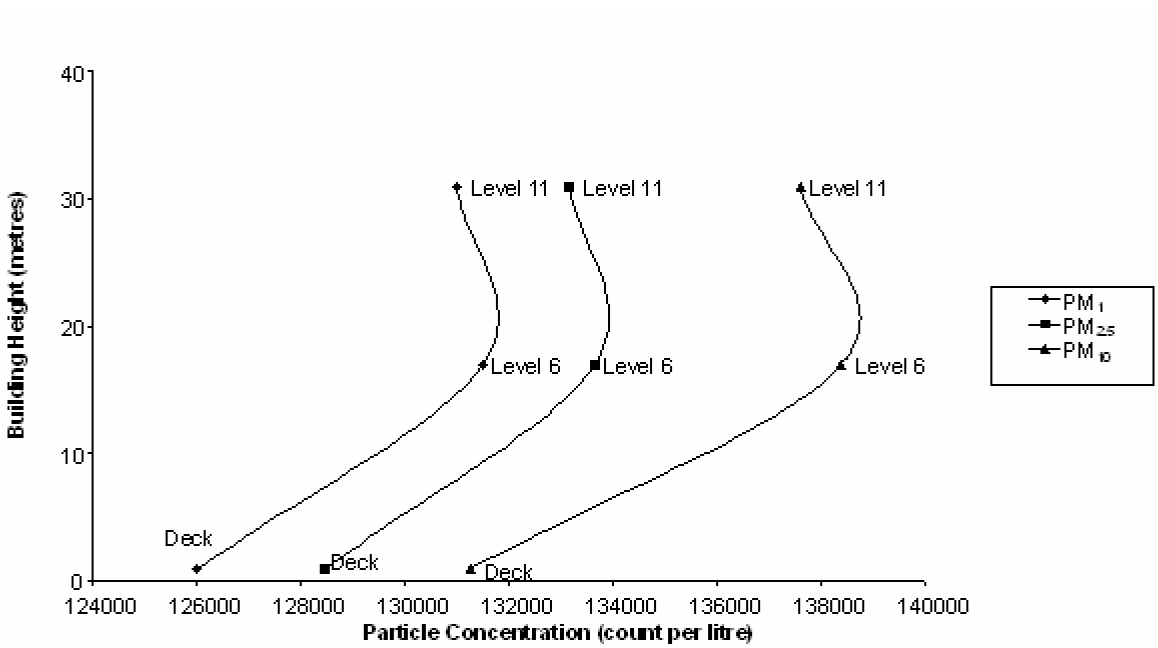

Figure 6-9 Variation of particle concentration with Building Height

Figure 6-9 shows the variation of particle concentration with height. The X- axis represents the particle concentration (count per litre) and the Y- axis represents the height (in metres). The graph represents the variation of concentration from deck, level 6 and level 11 for PM_1, $PM_{2.5}$ and PM_{10}. It could be observed that as the height increases the particle concentration first increases, attains a maximum value and then decreases. The particles are initially lifted up due to buoyancy and tend to rise. In their journey up, the fine particles may undergo changes in shape, size and composition. There is a possibility that they may be held in suspension at some heights. Considering this if the correlation of fine and coarse mode particles (which are considered to be primary in origin) is seen it is observed that level 6 has the lowest correlation followed by level 11, deck and bus stop. Table 6-3 summarizes the correlation between the fine and coarse mode particles.

Table 6-3 Correlation between fine and coarse mode particles

Location	$PM_{2.5}$ & $PM_{2.5-10}$
Deck	0.2669
Level 6	0.2177
Level 11	0.2493
Bus Stop	0.3065

A comparatively higher correlation is found at level 11 in comparison to level 6. This implies that fine and coarse mode particles are closely related as compared to level 6. Another reason as discussed earlier could be the tree cover that extends till level 6. Trees and vegetation are considered to be a source of deposition of particles which can lead to modification in particle characteristics. The highest correlation between fine mode particles and coarse mode particles and the highest PM_1/PM_{10} ratio is observed at the bus stop. This suggests that bus stop is having most of the particles from combustion generated processes (vehicular exhausts). Also no other sources of fine particles were observed during the experiments.

6.3.2 Meteorological parameter profile at different Building heights

The meteorological parameters, i.e., temperature, relative humidity and wind speed, were measured at each of the measuring location along with particle concentration. Figure 6-10 shows the variations in wind speed with the height of building.

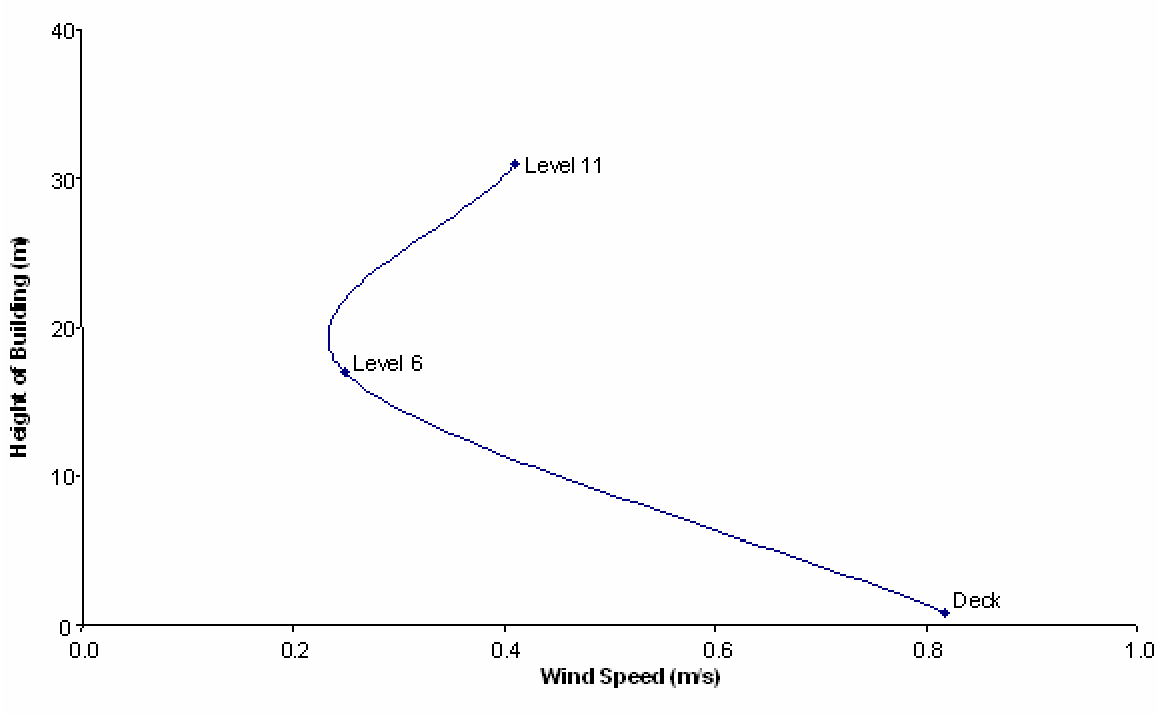

Figure 6-10 Variation of Wind Speed with Building Height

It is observed that level 6 has the lowest wind speed in comparison to deck and level 11. This may be responsible for high concentration of particles in the coarse mode (above 2.5 µm), as the particles are not removed by the wind speed and remained in suspension. Deck has the highest wind speed and the lowest fraction of coarse mode particles (i.e. the $PM_{2.5-10}/PM_{10}$ is lowest at deck as compared to level 6 and level 11). However, wind speed is not the only factor affecting the concentration of particles. There are other meteorological factors like temperature and relative humidity which also plays an important role. Figures 6-11 and 6-12 show the profile of temperature and relative humidity as a function of building height. Level 6 is observed to have the highest temperature and relative humidity. It has comparatively lower proportion of fine particles as compared to the deck. However larger size particles are not as effectively washed down as compared to fine particles and level 6 has a higher proportion of particles in the range of 2.5-10µm.

The concentration of particles is governed by a number of factors. Hence the correct estimation of particle concentration is a difficult task. There are some factors like solar radiation which may also influence the concentration of particles. Also as discussed earlier, particles is a complex entity with a number of sources. Different sources may have different affinity to these meteorological parameters. The difference in density between a soil grain and a water droplet is a factor of 2.5. Similarly particles of soot will behave differently as compared to that of salt. Also, particles in the accumulated mode will fuse to form bigger size particles. Apart from this, particle residence time and ageing will also depend on chemical and physical characteristics of particles. Hence there are numerous factors which will affect the particle concentration.

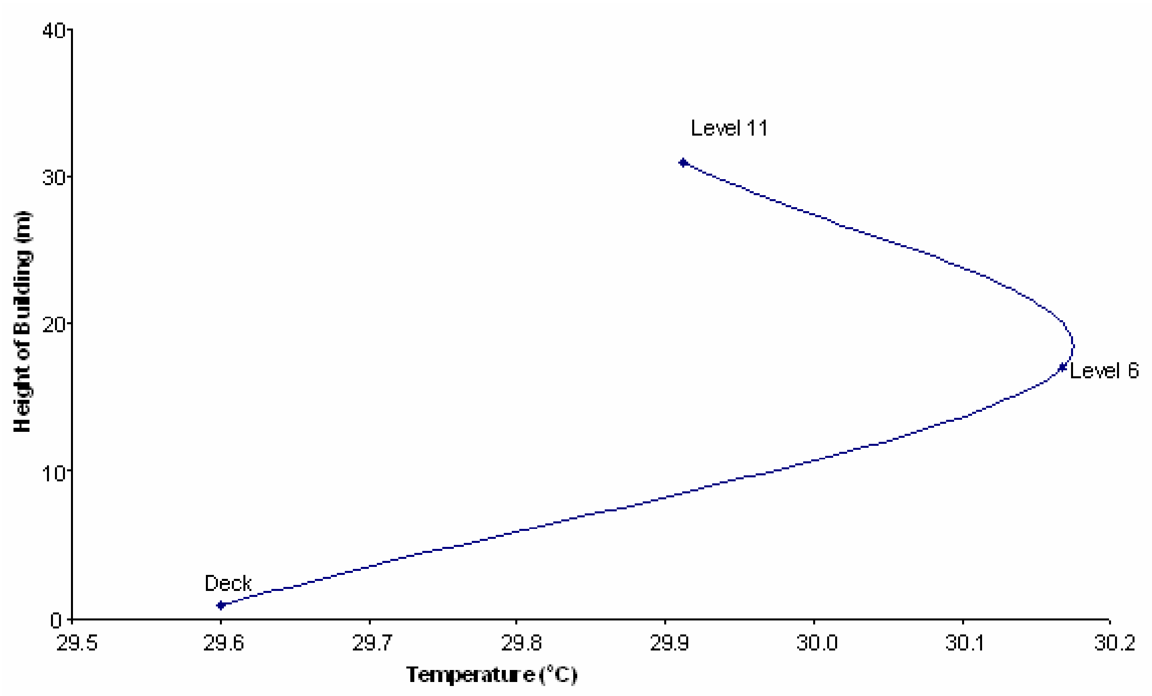

Figure 6-11 Variation of Temperature with Building Height

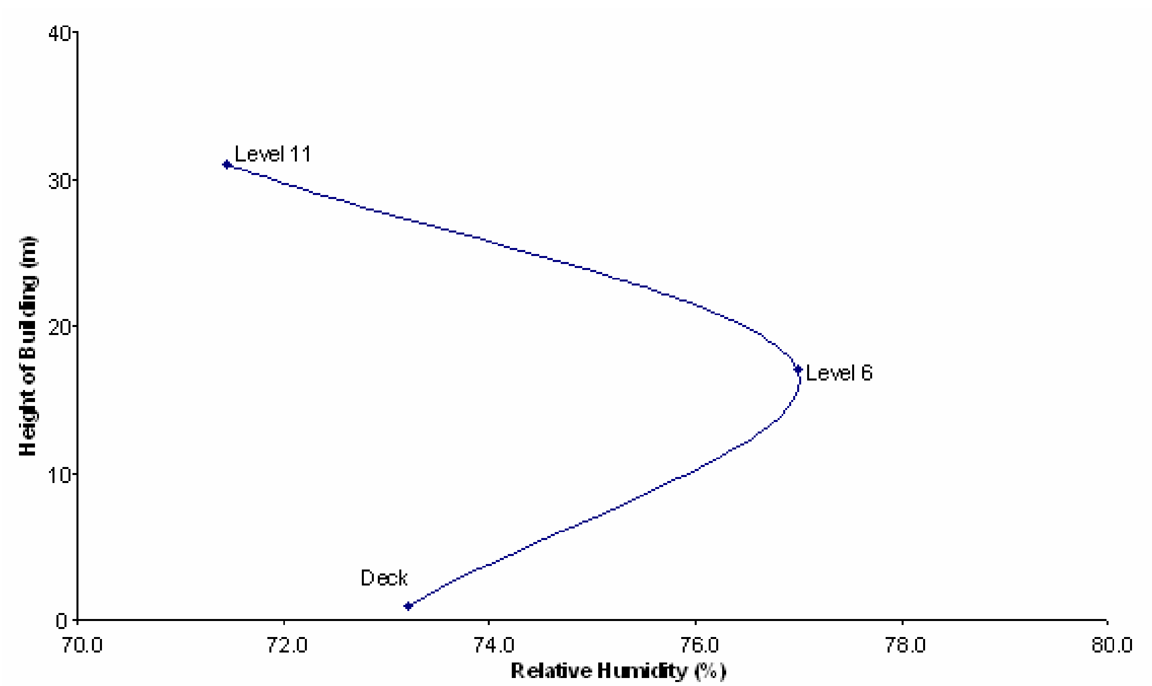

Figure 6-12 Variation of Relative Humidity with Building Height

6.4 Conclusions

The study revealed that the concentration of particles in a building varied with height, with first an increase in value, attains a maximum and then decreases. The difference in concentration for PM_1 was less as compared to PM_{10}. A similar study carried out in Hong Kong **(Chan et al., 2000)** with a building located in open street configuration reported similar results for buildings near the sea or places where sea breeze can cause a change in particulate level. In that study, the parameter study was PM_{10} and TSP and high level of TSP was reported at intermediate building heights. In the present study, a higher PM_{10} is observed at intermediate building height as compared to higher building height. A similar study in an industrial region in Mumbai, India **(Sharma et al., 1991)** showed that particulate concentration is maximum at around 9 m and a decreasing trend above this height for fine aerosols of sizes less than 3.2 µm

The correlation between fine and coarse mode particles at the intermediate building height was comparatively weaker as compared to higher building height. It was also observed that the temperature and relative humidity were highest and wind speed was lowest at the intermediate building height. There might be some fraction of particles which may undergo gravitational settling, another component replacing the settled particles but all these factors are tough to be computed mathematically. This can be stated in terms of the following equation where x represents the height.

$$C(x) = C_{(buoyancy)} - C_{(settling)} + C_{(suspension)}$$

In general, due to lack of obstructions, as in the case of tall buildings, dispersion of pollutant in the open street is influenced by wind speed, wind direction and proximity to major road. In the present study this was the major factor as the building is located just on the expressway. However a channeling effect for wind was observed due to the building blocks located at the back of the building.

Chapter 7: Conclusions

Particle is the pollutant of concern these days with the researchers. Particle is a complex entity and can be characterized in many ways. The present research work characterized particles in terms of mass and count. It is observed that fine particles comprise a significant proportion of the overall suspended particles.

In Singapore, there is a good network of expressways and roads to enable smooth and fast movement of people. It is observed that the concentration of PM_1 and $PM_{2.5}$ could comprise a significant proportion of $PM_{10.}$ At one of the major expressways, Ayer Rajah Expressway (LOC 1) the concentration of PM_1 and $PM_{2.5}$ was 60 % and 75 % of PM_{10} respectively. On some minor roads (LOC 2), PM_1 and $PM_{2.5}$ accounted for 45 % and 60 % of PM_{10} respectively. The higher concentration of PM_1 and $PM_{2.5}$ at the expressways can hence be attributed to the high vehicular traffic. Characterization of particles in terms of particle count showed that fine particles can comprise 99% of the suspended particulate matter. This shows that fine particles, which have the tendency to penetrate deep into the lungs, are much greater in numbers. These fine particles have a tendency to travel to long distances as compared to the larger size particles and are not much affected by gravitational settling.

The Indoor-Outdoor ratio of particles is also assessed for both naturally-ventilated and mechanically-ventilated locations. It is seen that the mechanically-ventilated spaces have a comparatively lower I/O ratio as compared to the naturally-ventilated locations. In addition larger size particles (2.5 microns and above) were nearly absent due to the filtration systems used in the mechanically-ventilated spaces.

In a naturally-ventilated building, ambient parameters like temperature, wind speed and relative humidity can play a significant role in effecting the migration of particles. Results show that wind speed and temperature have a positive influence on migration of particulate matter where as relative humidity has a negative influence on the transport phenomenon of particulate matter. Temperature may be a dominant factor governing the migration of fine particles as compared to wind speed. With the increase in size of particle their dependence on ambient parameters comparatively decreases more for temperature and relative humidity as compared to wind speed.

In Singapore, tall building structures are common and some of these buildings are located very close to expressways. The particle concentration at each building height will be different. It is observed that the concentration of particles first increases till intermediate building height and then decreases. This will also depend on the size of particles. Gravitational force may play a significant role for larger size particles. However, another possibility is that the particles can be kept in suspension due to the balance of gravitational force and buoyancy forces. This will therefore vary from location to location. However, the concentration at different building heights can also be effected by ambient parameters.

The present study has some limitations. The instrument, Grimm Dust Monitor, used during the experiments can not measure the particle count below 0.3µm. Hence the particles in the study are from 0.3µm - 10µm.

In the future studies, it will be advantageous to do the chemical characterization of the particles at different experimental locations. That will help in predicting the source of particles.

However in the present study, it is seen that at different experimental location there is a difference in particle distribution. For instance, there is a difference in particle distribution on an expressway as compared to a minor road, similarly a naturally-ventilated building as compared to a mechanically-ventilated building. This to some extent points to the type and possible characteristics of particles at these locations.

To conclude, *the behavior and characteristics of particles are difficult to determine as number of variables affect their nature, but this thesis has identified some of the key parameters that influence the migration of airborne particles from outdoor to indoor environments in Singapore.*

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List of Publications

GUPTA, A., CHEONG, K.W.D., WONG, N.H., 2003. Characterization of particulate matter in the tropics. International Conference on Healthy Building, Singapore 7-11 December 2003, Volume 2, pp 140-146.

GUPTA, A, CHEONG, K.W.D., WONG, N.H., 2004. How ambient environment affects the migrations of particulate matter?, ROOMVENT 2004 - 9th International Conference on Air Distribution in Rooms, Portugal 5-8 September 2004

ZHOU, W., THAM, K.W., ZURAIMI, M.S., GUPTA, A., 2004. Indoor air quality and thermal comfort studies in the tropics: a comparison between under-floor supply and ceiling-based mixing ventilation systems using female subjects, ROOMVENT 2004 - 9th International Conference on Air Distribution in Rooms, Portugal 5-8 September 2004

Appendix A

This appendix includes abstracts of the following publications:

- GUPTA, A., CHEONG, K.W.D., WONG, N.H., 2003. Characterization of particulate matter in the tropics. International Conference on Healthy Building, Singapore 7-11 December 2003. Volume 2, pp 140-146.

This paper reviews the exposure to particulate matter on bus stops during peak traffic hours. The methodology involves monitoring of Total Suspended Matter, PM_{10}, $PM_{2.5}$ and PM_1 using Grimm Dust Monitor for a period of five weekdays. Traffic flow and relevant meteorological parameters were also recorded. The exposure to particulate matter is critical since fine particles get deposited into the respiratory tract and can lead to various respiratory diseases and premature deaths. The study shows that PM_{10} comprises almost 80% of the total suspended particulate matter. PM_1 could comprises up to 83% of $PM_{2.5}$ which could be critical as surface number dose will be much higher for finer particles than for coarse particles. In addition it was observed that PM_1 gravimetrically comprises 62.2±4.9% of PM_{10} where as on basis of number density PM_1 comprises 99.5±0.3% of PM_{10}. The concentration of PM_1 is significant as it could have adverse health impacts on the lung with greater penetration. The infiltration of particulate matter into the building will depend on size of particulate matter, filtration characteristics, properties of building envelope etc. Hence there is a need to have further research in this area.

- <u>GUPTA, A</u>., CHEONG, K.W.D., WONG, N.H., 2004. How ambient environment affects the migrations of particulate matter ?, ROOMVENT 2004- 9th International Conference on Air Distribution in Rooms, Portugal 5-8 September 2004.

  The paper reviews the effect of environmental parameters on the migration of particulate matter. The methodology involves simultaneous monitoring of particulate matter using dust monitor at indoor and outdoor locations along with the ambient environmental conditions. The study is of great significance as Particulate Matter (PM) has been reviewed in terms of particle count, which is more significant as compared to particle mass. In this paper, the variation of Indoor (PM) /Outdoor (PM) calculated on the basis of count are studied as a function of ambient wind speed, temperature and humidity. Further detailed characterization of the PM on the basis of count is done to signify the importance of fine particles specifically PM1 in comparison to PM10. This study can help in designing ventilation strategy for naturally-ventilated buildings. Similar studies can help in selecting fresh air intake points for mechanically ventilated buildings in order to minimize the migration of air pollutants into the indoor environment.